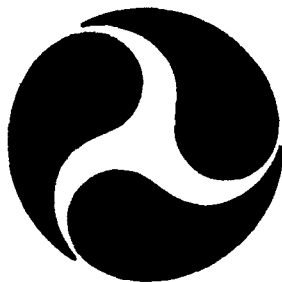AD-A281 786

Report No. CG-D-08-94

EVALUATION OF
PERSONAL MULTIGAS MONITORS

Kenneth R. Carney
Aaron M. Mainga
Xianzhong Zhang
Edward B. Overton
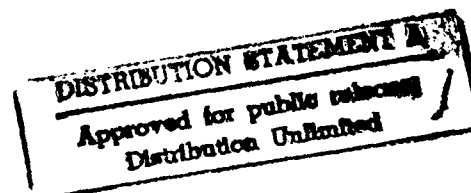Rene V. Arenas

Louisiana State University
Institute for Environmental Studies
Baton Rouge, LA 70803

National Oceanic and Atmospheric Administration
Hazardous Materials Response and Assessment Division
Seattle, WA

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15. Supplementary Notes

The Coast Guard technical contact and COTR is Dr. Alan Bentz, (203) 441-2817.

16. Abstract

Eight different makes of multigas monitors were evaluated for use by U.S. Coast Guard field personnel. The meters were evaluated with regard to: linearity of response to methane, oxygen and hydrogen sulfide levels; ability to do remote sampling, accuracy for each type of gas; alarm response time, portability, bulk, eight (8) hour battery charge (for NiCad versions) [dry cell versions also tested when available]; ease of use; temperature and humidity effects, and resistance to shock of impacts. Two of the instruments wre significantly better than the rest in most respects.

17. Key Words		18. Distribution Statement
personal monitors multimeters oxygen meters explosion meters hydrogen sulfide meters NiCad memory	impact resistance precison accuracy remote sampling alarm response time portability	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

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I. INTRODUCTION

A. Background

The purpose of this work was to evaluate fieldable, direct-reading, multisensor gas detectors designed for the continuous monitoring of ambient air quality in the workplace. These devices, commonly known as personal multigas monitors, allow personnel working in confined spaces (e.g., ship compartments, storage tanks, silos, manholes, pipelines, etc.) to monitor the air quality in the enclosed area prior to entry and during the work period. The utility of these devices, however, is not limited to enclosed spaces, but also applies wherever toxic or flammable gases may be present (i.e., for general industrial hygiene and safety).

Multigas capability for the monitors is achieved through the use of specific sensors for each gas type. Hence, monitoring of the different target gases in the air is carried out independently for each individual gas. The principles of detection for the various sensors employed have recently been reviewed[1], and a reprint of that paper is attached (Appendix A). Those not familiar with the technology utilized for these gas sensors are encouraged to read Appendix A before reading this report. Knowing what types of sensors are installed and understanding how they work will enable the user to identify the capability and limitations of the multimeasurement device. As indicated by Wheeler,[2] even with all of the technological advancements (mainly in the electronics and software incorporated in the instruments) found in state-of-the-art gas monitors today, utility of the portable monitor as a safety device is still sensor-limited. Another review paper[3] (Appendix B) identifies the desirable features of an ideal combination gas monitor for confined space application, presents a survey of the different models available in the U.S. as of March 1992 (including models not evaluated in the present study), and describes the features of those models.

The monitors evaluated are intended to be used as a detection device for personnel safety and not as a quantitative analytical instrument. It should be noted that "detection" implies recognition of a significant quantity of the target gas, while "analysis" implies a quantitative assessment of the amount of target gas in the sample.[4] The primary objective for their use is for safety and protection. Hence, the monitor is designed to be conveniently worn or carried by the worker at all times (i.e., within the person's breathing zone) while inside the confined space or working area. At present, however, the use of these gas monitors has become a necessity not only for protecting personnel from exposure to the dangers of oxygen deficiency or excess, and the presence of toxic and flammable gases,

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but also for complying with the new confined space law (29 CFR 1910.146 - "Permit Required Confined Spaces") issued by OSHA (Occupational Safety and Health Administration) in February 1992.[5-8] According to a recent survey conducted by OSHA,[7] many deaths and injuries in confined spaces are caused by atmospheric hazards. These are classified into three categories, namely: (1) toxic (with hydrogen sulfide and carbon monoxide being the most commonly encountered in confined areas), (2) asphyxiating, and (3) flammable or explosive atmospheres. Hence, the new law requires testing of the confined space atmosphere for these gases.

Finally, this study was limited to portable monitors equipped with small, plug-in sensors designed to continuously and simultaneously detect the spot concentrations of at least the following gases: oxygen (O_2), toxic gas (specifically hydrogen sulfide or H_2S), and combustible gases. Hence, only monitors that can accommodate at least three gas sensors simultaneously were evaluated. For those interested in further readings about the toxicological effects or injuries resulting from exposure to various levels of O_2, H_2S and combustible gases (especially CH_4), and potential sources for the occurrence of these hazards, the readers are referred to the following references.[1, 9-16] The main objective of the research was to evaluate the various detection capabilities, operational parameters, and *physical characteristics* of ten models of portable, combination gas monitors in terms of response linearity, sensor selectivity, alarm response time, remote sensing capability, portability, ease of operation / maintenance, cost, and other value added features. Based on these results, the meters were ranked according to their overall suitability for use as personal safety monitors in confined and hazardous work areas.

B. State-of-the-Art Gas Monitors for Confined Spaces

Before proceeding to a discussion of methodology and analysis of the results obtained, some preliminary information is provided concerning the requirements for an ideal, multisensor gas meter for use in confined space monitoring. The significance of each of these desirable features is also discussed, as well as a brief description of the different variations that can be found in state-of-the-art monitors that manufacturers use to satisfy these requirements. The information presented was acquired and pooled from several product catalogs, instrument instruction manuals, and most importantly, from personal communications with various company representatives and industrial hygienists.

A listing of the desirable features for an ideal, multisensor gas monitor for confined space analysis has been published[3](see Table 1 of Appendix B). Following are the

specifics for these different features. It should be noted that the sequence used does not imply any order of importance for these features.

1. Sensor Response

The accuracy, speed, selectivity, sensitivity and reproducibility of the meter response for a given gas is dependent on the particular sensor type employed. Typical values for the different sensor types for these parameters have already been published (see Appendix A).[1] It is emphasized, however, that the monitor response to a given gas can only be as good as the sensor employed. Hence, it is important to know beforehand what sensor types are installed to determine the capabilities and limitations of the device.

2. Microprocessor Control

State-of-the-art, portable gas monitors differ from their older counterparts mainly in terms of the microprocessor and softwares installed in today's meters.[2] Incorporation of microprocessor technology into the system has revolutionized these instruments, providing simple operation (e.g., automatic diagnostic check, automatic zeroing and automatic calibration), data storage capability, and the ability to perform electronic calculations (e.g., averaging). Because of the two latter features, state-of-the-art gas meters now can perform the following tasks: (1) store and display peak values, (2) function as a dosimeter through the calculation of TWA data, and (3) determining exceedances of TWA, STEL, TLV (threshold limit value),are exceeded, as well as ceiling limits. Some monitors also function as data loggers, allowing the operator to download all the information collected and stored during a monitoring period to a computer for further analysis. Examples of the kind of data stored are ambient temperature, instrument operating time, TWA exposure to toxic gases, peak or highest levels encountered, number of alarms, and sensor reading for each gas analyzed at one minute intervals for the entire period that the instrument was used.[3]

3. Operation and Maintenance

The desirable monitor is "user-friendly"; it is easy to operate (with easy-to-understand manuals) and requires minimum maintenance. For these units the procedures an operator needs to learn include: (1) zeroing in "clean" air, (2) span calibration, (3) setting of alarm points to the desired levels, (4) sensor replacement, and (5) battery charging or replacement. The fourth procedure is accomplished by simply mounting and locking the sensor in place. Sensor replacement has even been simplified to the point that a pre-programmed and pre-calibrated sensor can be installed in the field for immediate use. This

capability allows the user to choose and install the appropriate toxic gas sensor (e.g., H_2S, CO, SO_2, Cl_2, H_2, NO, NO_2, HCN, HCl and NH_3) required, hence upgrading a three to five sensor instrument at minimum cost. In general, easy-to-operate monitors are those for which zeroing, span and alarm calibrations can be achieved without opening the instrument to adjust potentiometers and are usually carried out using menu-driven procedures. This allows the performance of these tasks to be done easily in the field. More sophisticated systems even allow the operator to choose between two or three operating modes, with each mode varying in difficulty or in the operator technical skill required. For example, a basic mode is available, designed for personnel with minimum training and experience, wherein the monitor simply tells the worker whether the environment is safe for continued work. In contrast to this, an advanced mode allows more complicated procedures like calibration, setting of TWA and STEL alarm points, and downloading data to a computer.

As a final note, however, it is emphasized that no area monitoring should be performed without verifying the calibration of: (1) pre-calibrated sensors, and (2) monitors which have been span calibration automatically. Specifically, periodic . namic calibration of the instrument with the target analyte should be performed by qualified personnel (i.e., certified industrial hygienists) prior to actual sampling. Only then can untrained people be able to judge using these monitors whether or not an environment is "safe" for continued occupation.

4. Remote Sampling or Sensing Capability

Remote sampling capability is achieved through the use of either (a) a built-in or attachable (motorized or manual) sampling pump which draws air samples from the confined or remote space, or (b) an extension cable with the appropriate sensors mounted in a housing fitted at the end of an extension pole or rope where the monitor can be mounted or attached. Hence, in the second procedure either the entire monitor or just the sensors are lowered into the contaminated atmosphere. Typical tube lengths vary, and can be 30 meters long. The geometry of the enclosed area should be considered whenever remote air sampling is performed prior to entry into a confined space. A "safe" result for a sample in the middle of, e.g., the cargo hold of a ship, does not mean the entire volume is safe;enclosed spaces are frequently not homogeneous.

5. Alarms

Visible (usually a red, blinking LED) and audible alarms are used primarily to warn the personnel if preset gas levels have been exceeded. In some instruments, the alarm remains

locked or "latched" until the operator resets the monitor in "clean" air, while others allow the user to silence the audible alarm for a short period of time. At least one monitor model currently available is even equipped with an above 100% LEL latching alarm designed to protect the worker from the erroneously low readings obtained when using catalytic combustion sensors at combustible gas concentrations above the upper explosive limit (UEL).[1, 24] Alarms are also available to warn the worker of low battery power, and sensor or circuit malfunction. Some instruments are even equipped with earphones for use in noisy environments. Better instruments will, however, have both low and high oxygen alarms, and at least two alarm levels for toxic and combustible gases. More so: ated systems also allow the operator to set three more alarm levels corresponding to i. WA and STEL values, and the ceiling limit for a particular toxic gas.

6. Display

The best monitors are those which simultaneously display a continuously updated digital readout of all gas concentrations in the air being monitored. Digital readings are normally displayed in the following increments: 0.1% by volume oxygen, 1 ppm (*unless otherwise specified, all ppm values are v/v throughout this report*) toxic gas, and 1% LEL or 1% by volume combustible gas. The display must be easy to read, and equipped with back-up lighting which automatically turns on when ambient lighting becomes inadequate. For monitors which display only one gas concentration at a time, the display indicates which gas(es) have exceeded the pre-set level(s) during alarm conditions. Some models even have a "hold" switch which allows the meter to display only the highest concentration encountered. This latter feature, together with "latching" alarms, are extremely important for remote sensing and determination of target gas concentrations prior to entry.

7. Ruggedness and Durability

The ideal monitor to use is one which is reliable even when exposed to rough handling or extreme weather conditions. Hence, these instruments must be weather-resistant, shock/vibration-resistant, and thermally stable. The monitor must be water-resistant, and should operate properly during conditions of at least 0 to 40° C, and between 0 to 99% relative humidity (non-condensing).

The "ON/OFF" and calibration buttons must also be protected from accidental shut off and unintentional changes, respectively. To prevent accidental shut off, three mechanisms are commonly employed, namely: (a) a protective cover concealing the "ON/OFF" switch, (b) a three to five second turn-off delay, or (c) two separate controls for turning the monitor

off. To protect the calibration knobs from being unintentionally altered, these controls may be located inside the instrument or concealed by a protective cover which can be easily removed without opening the monitor body. For menu-driven procedures, protection from inadvertent changes can be achieved through the use of more than one button or steps. In some instruments, prevention of unauthorized tampering of calibration and alarm points, on the other hand, are achieved through the use of a password.

Ruggedness and durability also results from the use of high-quality gas sensors, which do not easily leak (for the electrochemical sensors), and are poison-resistant (for the catalytic combustion sensor). The sensors should also be located so as not to allow any solid materials (e.g., grease, tar, paint, mud, etc.) to accumulate at the sensor compartment or cover and affect the sensor response. Finally, the use of a sturdy enclosure material (usually stainless steel, aluminum, or high impact plastic), and carrying case also enhances the durability of the device.

8. Safety Features

Ideally, the monitor should be electrically, mechanically, and functionally safe.[25] That is, the instrument must not (1) serve as a potential source of ignition, (2) produce a spark when dropped, and (3) break open exposing sparks generated by the instrument (especially the catalytic combustion sensor); and should warn the user if the monitor is no longer functioning or operating properly (i.e., "fail-safe"). The first three criteria are important in worksites where flammable/explosive substances are normally handled. The "fail-safe" feature is also essential for the sampling pump since the worker should be warned if any flow interruptions or failure has occurred to avoid false low readings. Similarly, automatic monitor shut-off during conditions of insufficient battery power is essential since not only does this prevent battery damage, but this feature also inhibits the monitor from providing false readouts. Finally, the monitor should be protected from false detection resulting from radio frequency interference.

The safest monitors to use are those that have been certified by independent organizations like the British Approvals Service for Electrical Equipment in Flammable Atmospheres (BASEEFA), Canadian Standards Association (CSA), Electrical Testing Laboratories (ETL), European Committee for Electrotechnical Standardization (CENELEC), Factory Mutual (FM), Mine Safety and Health Administration (MSHA), Underwriters Laboratory (UL), etc., as intrinsically safe to use in flammable/explosive atmospheres (most commonly for use in Class I, Division I, Groups A, B, C, and D hazardous conditions).

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9. Battery Pack

A rechargeable battery pack or disposable dry cells are commonly used as power source, the most important feature of which is that it should provide at least 8 hours of continuous operation even with the sampling pump on. Other desirable features are that batteries should be easily changeable, and that, for rechargeable batteries, recharging can be carried out even with the battery pack disconnected from the monitor. Finally, the monitor should allow the user to determine at any time how many useful battery hours still remain (i.e., before battery recharging or replacement is needed) for proper functioning, which in some instruments is easily accomplished with the push of a button. Some monitors are, however, equipped only with low battery power alarms.

For instruments equipped with rechargeable batteries, the battery charger should automatically go to "trickle" charge to prevent battery damage resulting from overcharging. The charger should also be capable of fully charging the battery overnight. Some monitors also provide optional vehicle charging adapter so the device can be recharged using a vehicle's cigarette lighter.

10. Portability

Since the detector is designed to be worn or carried by the user at all times while inside the confined space, the ideal monitor is light in weight, and small in size for easy, convenient handling. Portability is achieved through the use of either a wrist strap, belt clip or strap, or shoulder strap, with or without a carrying case. Most instruments can also be purchased with an optional plastic carrying case which can contain not only the monitor, but also the calibration kit, sampling pump and accessories, extra sensors, extra battery pack, tools, and operation manuals.

II. EXPERIMENTAL

A. Instruments Evaluated

A listing of the different gas monitors evaluated at the Institute for Environmental Studies (IES) at Louisiana State University (LSU) is shown in Table 1. The different models evaluated were selected by the U.S. Coast Guard Research & Development Center in Groton, CT. Generally, two samples of the each model were provided. Only one each of the CGS-80, CGS-90, Compur Tritox D and Compur Tritox M models was supplied. Additionally, although two HMX271 and two MiniGas monitors were provided, one of each was powered with rechargeable NiCd batteries and the other with alkaline dry cells.

As can be seen from Table 2 of Appendix B, there are currently at least sixteen manufacturers or distributors and at least 48 models of portable combination gas monitors (i.e., monitors which can contain simultaneously at least three sensors).

The present study, however, includes only ten models (out of 48) from eight manufacturers (out of sixteen) listed in Table 2 of Appendix B. Note that the NiCd and Dry Cell versions (i.e., for the HMX271 and MiniGas monitors) were counted only as one model since these meters are essentially the same differing only in the power source utilized. Some of the features of the monitors evaluated (the most important of which are the gases that can be monitored, the corresponding applicable concentration ranges, and sensor type employed) are shown in Table 2. The entries listed in Table 2 were based on information provided voluntarily by the manufacturers of these devices, and were obtained from reference 3.

Table 1. List of portable, combination gas monitors evaluated.

	Manufacturer or Distributor [a]	Model [b,c]	Serial Number(s)
1.	Biosystems, Inc.	PhD Atmospheric Monitor Model 1602 [PhD]	DK108-1428 DK108-1429
2.	2.Dynamation, Inc.	Dynamation CGM Model 929A [CGM929A]	4571 4572
3.	Enmet Corp.	CGS-80	5872
4.	Enmet Corp.	CGS-90	630
5.	GfG Gas Electronics, Inc.	Polytector G700/3 [G700]	91090289 91090290
6.	Industrial Scientific Corp.	HMX271 (NiCd) HMX271 (Dry Cell)	9106081-105 9106084-034
7.	Miles, Inc.	Compur Tritox D	2596
8.	Miles, Inc.	Compur Tritox M	2688
9.	Neotronics of North America, Inc.	MiniGas (NiCd) MiniGas (Dry Cell)	000375 000412
10	Scott Aviation	Scott-Alert Model S108 [S108]	9136-1634 9136-1656

[a] Company addresses: • Biosystems, Inc., P.O. Box 158, Rockfall, CT 06481; • Dynamation, Inc., 3784 Plaza Drive, Ann Arbor, MI 48108; • Enmet Corp., 680 Fairfield Ct., P.O. Box 979, Ann Arbor, MI 48106-0979; • GfG Gas Electronics, Inc., 6617 Clayton Rd., Suite 209, Clayton, MO 63117; • Industrial Scientific Corp., 1001 Oakdale Road, Oakdale, PA 15071; • Miles, Inc., Compur Monitors, 7015 West Tidwell, Suite G106, Houston, TX 77092; • Neotronics of North America, Inc., 2144 Hilton Drive, P.O. Box 370, Gainesville, GA 30503-0370; • Scott Aviation, A Figgie International Company, 225 Erie Street, Lancaster, NY 14086.

[b] All monitor models evaluated sample the atmospheric air by diffusion except the Compur Tritox M which is equipped with a built-in, motorized sampling pump which is operational at all times that the meter is "ON". The G700 meter also has a similar motorized pump which can be switched "ON" and "OFF" by the operator.

[c] Abbreviations in square brackets were used to designate some monitor models in the text. For example, PhD in the text was used to designate the PhD Atmospheric Monitor Model 1602 manufactured by Biosystems, Inc. Alternately, for models with two monitors provided, monitor #1 corresponds to the version with the lower serial number while monitor #2 corresponds to that with the higher serial number.

Table 2. Features of the portable, multisensor gas monitors evaluated.[a]

Manufacturer / Distributor	Model Series	Max. No. of Simultaneously Installed Sensors[b]	Gases Monitored[c]	Concentration Range[d]	Sensor Type[e]	Simultaneous Digital Display of All Gas Levels?[f]	Built-in Sampling Pump?[g]	Data Logging?[h]	Dimensions, L x W x H (cm)	Weight[i] (kg)
Biosystems	PhD	4	O2	0-25%	Electrochemical	Yes	No	Yes	18.3 x 10.9 x 5.6	0.6
			Combustibles	0-100% LEL	Catalytic					
			H2S	0-140 ppm or 0-675 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO2	0-500 ppm	Electrochemical					
			Cl2	0-7 ppm	Electrochemical					
			NO2	0-7 ppm	Electrochemical					
			HCN	0-200 ppm	Electrochemical					
			NH3	0-100 ppm	Electrochemical					
Dynamation	CGM929A	3	O2	0-25%	Electrochemical	Yes (Bar graph for toxic gas read-out)	No	Yes	20.3 x 11.4 x 5.1	1.8
			Combustibles	0-100% LEL	Catalytic					
			H2S	0-200 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			Toxic	0-9 units	MOS[j]					
Enmet[k]	CGS-90	3	O2	16-25%	Electrochemical	No (Bar graph for oxygen and combustible or toxic gases)	No	No	22.8 x 11.4 x 5.7	2.8
			Combustibles	0-25% LEL	MOS					
			H2S	0-25 ppm	MOS					
			CO	0-125 ppm	MOS					
Enmet[k]	CGS-90	3	O2	0-99.9%	Electrochemical	Yes (Bar graph for combustible and toxic gases)	No	No	19.2 x 11.1 x 6.1	1.6
			Combustibles	0-25% LEL	MOS					
			H2S	0-25 ppm	MOS					
			CO	0-125 ppm	MOS					
GfG Gas Electronics	G700	4	O2	0-25%	Electrochemical	No	Yes	Yes	21.7 x 9.0 x 6.0	0.9
			Combustibles	0-100% LEL	Catalytic					
				0-5% CH4						
			Combustibles	0-99.9%	Thermal Cond.					
			H2S	0-50 ppm	Electrochemical					
			CO	0-200 ppm	Electrochemical					
Industrial Scientific	HMX271	3	O2	0-30%	Electrochemical	No	No	No	12.1 x 7.0 x 3.8	0.6
			Combustibles	0-100% LEL	Catalytic					
			H2S	0-1999 ppm	Electrochemical					

Table 2 Features of the portable, multisensor gas monitors evaluated. (cont.)

Manufacturer / Distributor	Model Series	Max. No. of Simultaneously Installed Sensors [b]	Gases Monitored [c]	Concentration Range [d]	Sensor Type [e]	Simultaneous Digital Display of All Gas Levels? [f]	Built-In Sampling Pump? [g]	Data Logging? [h]	Dimensions, L x W x H (cm)	Weight [i] (kg)
Miles	Compur Tritox D	3	O_2 Combustibles H_2S CO SO_2 Cl_2	0-30% 0-50% LEL 0-100 ppm 0-300 ppm 0-20 ppm 0-5 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical Electrochemical	No	No	No	24.5 x 11.0 x 4.6	1.2
Miles	Compur TritoxM	3	O_2 Combustibles H_2S CO SO_2 Cl_2	0-30% 0-50% LEL 0-100 ppm 0-300 ppm 0-20 ppm 0-5 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical Electrochemical	No	Yes	No	24.5 x 11.0 x 4.6	1.2
Neotronics	MiniGas	3	O_2 Combustibles H_2S CO	0-25% 0-99% LEL 0.05 to 4.95% 0-499 ppm 0-999 ppm	Electrochemical Catalytic Electrochemical Electrochemical	No	No	No	16.2 x 7.2 x 4.2	0.9
Scott/Aviation	S108	3	O_2 Combustibles H_2S	0-25% 0-100% LEL 0-199 ppm	Electrochemical Catalytic Electrochemical	No	No	No	15.9 x 7.9 x 4.1	0.5

a   Obtained from reference 3.

b   The maximum number of sensors that can be installed simultaneously does not necessarily equal the total number of gases that the instrument can monitor. Normally, for instruments which can accommodate more than three sensors simultaneously, the user has a choice of which toxic gas(es) to monitor.

c O_2 = Oxygen; H_2S = Hydrogen Sulfide; CO = Carbon Monoxide; CO_2 = Carbon Dioxide; SO_2 = Sulfur Dioxide; Cl_2 = Chlorine; NO = Nitrogen Monoxide or Nitric Oxide; NO_2 = Nitrogen Dioxide; H_2 = Hydrogen; HCN = Hydrogen Cyanide; HCl = Hydrogen Chloride; NH_3 = Ammonia.

d   % = present by volume; % LEL = percent of the Lower Explosion Limit (LEL); CH_4 = Methane; C_5H_{12} = Pentane; ppm = Parts per million.

e   MOS = Metal Oxide Semiconductor sensor; Catalytic = Catalytic combustion sensor. For more information about the different sensor types listed, refer to reference (5).

f   Read-out is digital, unless indicated otherwise.

g   Determining whether or not the device has a built-in sampling pump is ambiguous since in some models an "external" pump can be clipped or attached onto the instrument and be powered by the monitor's battery pack. However, all the models can be purchased with an optional sampling pump. Hence, all the instruments listed can be used for confined area monitoring.

h   Data logging capability is not a necessity for confined atmosphere monitoring.

i   The weights indicated are approximate values since it is not known what battery pack or sensors were installed.

j   The CGM929A monitor supposedly has an MOS sensor which responds to hundreds of toxic gases.

k   All CGS series instruments are available with an "industrial calibration", set up for toxic and combustible levels of hydrocarbon.

B. General Procedures

Prior to each experiment, the monitor was allowed to warm up in clean, ambient laboratory air for at least thirty minutes. Afterwards, they were "zeroed" in the same atmosphere; the oxygen, toxic gas and combustible gas sensor readings were set to 20.9% O_2, 0 ppm H_2S and 0% LEL (lower explosive limit) methane (CH_4), respectively.

Additionally, a span calibration of the toxic and combustible sensors was performed (every two weeks) using standard mixtures of 18 ppm H_2S or 30% LEL CH_4 in air, respectively. An exception to the latter procedure was employed for the combustible gas sensors of the CGS-80 and CGS-90 meters, which were span calibrated using 16% LEL CH_4, and for the toxic and combustible gas sensors of the CGM929A meters which were span calibrated using the manufacturer-supplied calibration gas (see set-up in Fig. 1) which contained 50% LEL CH_4 and 200 ppm carbon monoxide (CO). Note that in the latter case, although the CGM929A was span calibrated using 200 ppm CO, the monitor was programmed to read ppm H_2S with the toxic sensor expected to display 59 ppm H_2S for the 200 ppm CO calibration mixture. It should also be noted that based on manufacturer specification, in general the span calibration of the latter two sensors can be done approximately every four weeks. It is also emphasized that in the remaining text the term toxic gas refers to hydrogen sulfide (H_2S), unless indicated otherwise, and that methane was used to calibrate the combustible gas sensor for all monitors.

The span calibration procedure for the combustible and toxic gas sensors was carried out by first placing the monitors inside a disposable glove bag (Instruments for Research and Industry, Inc., Cheltenham, PA) which is made of polyethylene with gloves and one or two twelve inch equipment entrance sleeve(s). This type of test chamber was selected because it was less expensive than conventional, rigid glove boxes and is inflatable, hence requiring less gas for purging and analysis but still providing enough room for equipment and accessories. Additionally, all the monitors were exposed to the same test gas during calibration (and during other experiments wherein the meters were kept inside the bag), eliminating errors due to the use of manufacturer-supplied calibration gases. For example, for the span or sensitivity calibration of the combustible sensor, the supplied span gas for the HMX271 contains 25% LEL pentane while that for the G700 utilizes 40% LEL CH_4. All the air inside the bag was evacuated using a vacuum pump (Duo Seal Vacuum Pump Model 1402, The Welch Scientific Company, Skokie, IL), and then replaced with the test mixture. This evacuation and filling up process was done three times to ensure that all of the original gas inside the bag has been replaced with the test gas. The sensors were then allowed to equilibrate in the test gas atmosphere for at least thirty minutes (see Fig. 2), after

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which the monitor readout was adjusted to appropriate values (i.e., 18 ppm H_2S and 30% LEL CH_4 for the toxic and combustible sensors, respectively, unless indicated otherwise). A similar filling procedure was used for measurements in the test gas mixture (e.g., for the evaluation of the accuracy of the sensor response).

In general, three or four readings were obtained, unless indicated otherwise. All standard gas mixtures used were purchased premixed and certified from Liquid Carbonic Specialty Gas Corporation (Baton Rouge, LA). Also, unless stated otherwise, air sampling for the monitors was carried out by passive diffusion, and all measurements were conducted at ambient conditions. Additionally, except for experiments to determine the alarm response time (e.g., during the evaluation of response linearity), the different alarm points were adjusted so as to be out of range of the target gas concentrations if possible. The latter was done so as not to trigger the alarm (which can be annoying), thus extending the useful time of the battery charge. In cases where the alarm could not be silenced (e.g., for the MiniGas monitors which have fixed alarm points), earmuffs were used to prevent hearing loss due to the audible alarm. Finally, all experiments involving the use of H_2S were performed inside a fume hood. This additional precaution was necessary because of the very low TWA (time-weighted average) and ceiling limit set by OSHA for H_2S (i.e., 10 and 20 ppm H_2S, respectively).[17]
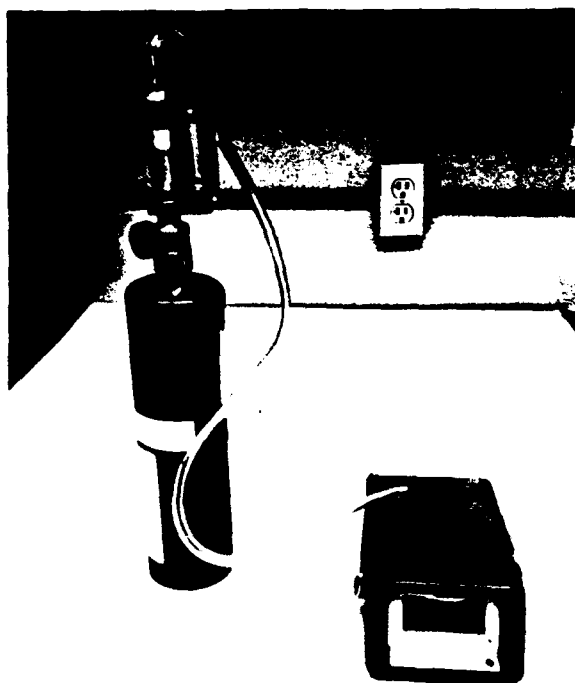
FIGURE 1.   Set-up for span calibration of the CGM929A monitors. A similar set-up is suggested by the instrument manufacturers for the normal span calibration of the combination gas monitors.
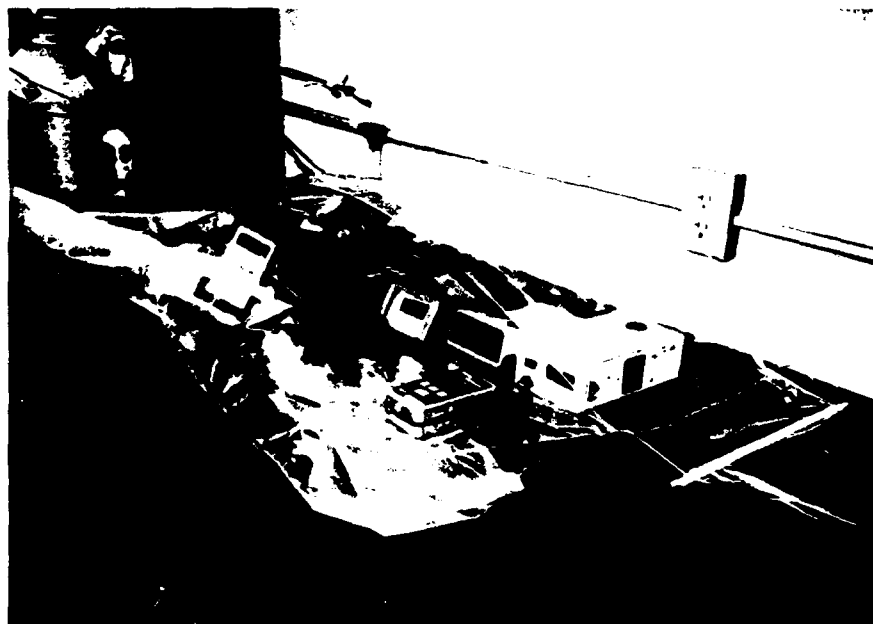
FIGURE 2.   Set-up employed for span calibration of the different combination gas
              monitors. A similar set-up was used for measurements wherein the
              monitors were to be placed inside the glove bag. The glove bag illustrated
              (part number SS-30-20H, Instruments for Research and Industry, Inc.,
              Cheltenham, PA) has dimensions of 30" x 20" x 14", two gloves, two
              equipment entry sleeves (one of which was originally sealed), and two gas
              tubulations (one connected to the test gas source [located on the upper left
              corner of the diagram], and the other to the vacuum pump).

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C. Evaluation of Detection Capability

1. Accuracy of Sensor Response

To determine the operating concentration ranges and the accuracy of the response, the instruments were placed inside the glove bag filled with the appropriate test gas mixture (see Fig. 2), and the monitor readout recorded after equilibration. Four readings were obtained, with the last value recorded after at least twenty minutes of exposure time after equilibration. To minimize cross contamination between the different test gases used, the most dilute mixtures were tested first and the more concentrated systems were tested later. Overall, three sets of data were collected approximately one month apart.

For the oxygen sensor, response was evaluated using gas standards containing 16.08, 19.58, 21.19, and 25.45% oxygen by volume in dry nitrogen (N_2). It should be noted that all gas concentrations that follow are specified in percent by volume (% v/v), unless stated otherwise. The average concentration of oxygen in breathing air is approximately 21%, while the 1991 OSHA definition of an oxygen deficient and oxygen enriched atmosphere is one wherein the concentrations of oxygen are below 19.5 and above 23%, respectively.[18] Hence, the oxygen concentration range employed in the study (i.e., from 16 to 25%) includes both the low (19.5%) and high (23%) oxygen alarm points commonly used for these monitors. Importantly, five of the ten monitors evaluated are capable of detecting oxygen only within the range of 0 to 25% (i.e., S108, G700, PhD, CGM929A, and MiniGas as indicated in Table 2). The bar graph display of the CGS-80 is limited to only 16 to 25% oxygen. Additionally, as indicated in the conclusions section of reference [1], "when the alarm is triggered, signaling the existence of potentially hazardous conditions, site evacuation and other precautionary measures should be immediately performed." The latter statement implies that it is enough to know that the concentration of oxygen in the atmosphere is below 19.5% or above 23%, and that knowing what the quantitative values are at oxygen levels <19.5 or >23% is not essential. Therefore, it is not necessary to use test gases containing less than 16 or greater than 25% O_2 to determine both the operating concentration ranges and limits of detection for the O_2 sensors. Similar arguments also apply for the analysis of combustible and toxic sensor responses.

Linearity of the combustible sensor response, on the other hand, was evaluated using 5.1, 15.8 and 31.5% LEL methane in air. This range already includes the commonly used alarm point for combustible gases which is 10% LEL. Finally, linearity of the toxic gas sensor response was determined using mixtures consisting of 6.5, 18.1 and 35.1 ppm

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hydrogen sulfide in air. The latter range was selected based on the OSHA Final Rule Limits[17] for hydrogen sulfide which set the exposure limits for H_2S at: 10 ppm for the time-weighted average; 15 ppm for the short term exposure limit (STEL); and 20 ppm for the ceiling limit. Selected recommended limits by OSHA and ACGIH (American Conference of Governmental Industrial Hygienists), and LEL values for selected air contaminants are tabulated in Table 1 of reference[1] (see Appendix A).

2. Sensor Selectivity

All the monitors evaluated were equipped with an electrochemical cell as oxygen sensor (see Table 2). A diagram of the latter sensor type can be seen in Fig. 1 of Appendix A. Hence, no selectivity test was performed for the oxygen sensor since it is well established that the sensor response of the oxygen electrochemical cell is highly specific and linear from 0 to 30% O_2.[1, 12, 19-22] Unfortunately, a similar situation does not exist for the combustible and toxic gas sensors. As can be seen in Table 2, all the monitors were supplied with catalytic combustion sensors and electrochemical cells for the combustible and toxic gas sensors, respectively, except for the CGS-80 and CGS-90 models which were supplied with metal oxide semiconductors (MOS) as combustible and toxic gas sensors. The CGM929A monitor is even equipped with a fourth MOS sensor which supposedly responds to hundreds of toxic gases. Diagrams of the catalytic combustion sensor, toxic gas electrochemical cell and MOS sensor can be seen in Figs. 2-4 of Appendix A.

For the toxic gas electrochemical sensor, the effect of carbon monoxide (CO) on the hydrogen sulfide readout was monitored using a 50 ppm (or more accurately a 49.9 ppm) CO in air mixture. This is because although the toxic gas electrochemical cell exhibits a highly specific and linear response from about 0 to 50 ppm H_2S,[12] the sensor is known to respond to both H_2S and CO.[19] The MOS toxic gas sensor, on the other hand, is nonspecific and exhibits a nonlinear response.[22] Selectivity of the latter MOS sensor was monitored using a 50 ppm CO in air mixture, and a 30% LEL CH_4 mixture in air. It should be noted that for both toxic gas sensor types, the sensor was span calibrated using 18 ppm H_2S, except for the CGM929A monitor. Also, the sensor response of the toxic gas electrochemical cell to 30% LEL CH_4 was determined to demonstrate the specificity of the latter sensor type over the MOS sensor as toxic gas sensor.

Finally, both catalytic combustion and MOS sensors which function as combustible gas sensors are nonspecific, although state-of-the-art catalytic combustion sensors exhibit a linear response up to at least 100% LEL.[1] One major limitation of the catalytic sensor,

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however, is that the sensor cannot detect combustible gases in the absence of oxygen. Hence, sensor selectivity was monitored using the following standard gases: 30% LEL pentane in air; 31% LEL CH_4 in nitrogen (i.e., with 0% O_2); 31% LEL CH_4 in 19.5% O_2 with nitrogen as the remaining gas; and 30% LEL CH_4 in air (i.e., with approximately 21% O_2). The latter three mixtures were used to monitor the effect of oxygen on the sensor response of both the catalytic combustion and MOS sensors. Again, all combustible gas sensors were span calibrated using 30% LEL CH_4.

3. Alarm Response Time

Alarm response time was defined as the elapsed time from gas exposure to the point when the alarm sounds when the meter is exposed to "bad" atmosphere. "Bad" atmosphere in this case refers to conditions that cause the monitor readout to exceed pre-set limits for toxic gases, combustible gases, or oxygen. Unless indicated otherwise, the low and high oxygen alarm points were set at 19.5 and 23.0% O_2, respectively. Analogous values for the combustible and toxic gases were 10% LEL CH_4 and 10 ppm H_2S, respectively. A 16% oxygen in nitrogen mixture was employed to determine alarm response time to oxygen deficiency, while a 25% oxygen mixture was used for oxygen abundance. Similarly, standard gases consisting of 30% LEL methane in air and 35 ppm hydrogen sulfide in air were used to monitor the alarm response time for the combustible and toxic gas sensors, respectively. Finally, an Armitron stop watch (Gluck Corp., Hongkong) was used to determine the elapsed time from gas exposure to alarm.

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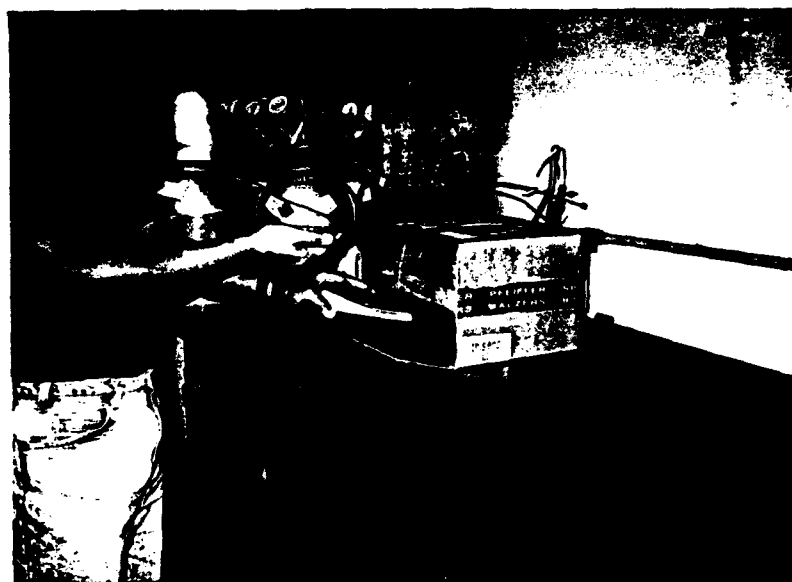
FIGURE 3.   Set-up for the determination of alarm response time using method #4 (see text) wherein the monitor was placed inside a small box (made of ordinary carton) previously purged with the test gas.

A "framework" of a box similar to that shown in Fig. 3 was placed inside the disposable glove bag (see Fig. 4). One of the meters was also kept inside the bag to monitor the gas concentration during the experiment. The collapsible "framework" facilitated evacuation of the glove bag, and allowed visual monitoring of the target gas

concentration in the bag with the reference monitor (i.e., the meter kept inside the bag) and the test monitor. For better reproducibility, two persons are required to perform the experiment: one in charge of opening the bag, then rapidly placing the meter inside the bag, and closing the bag; and a second person for measuring the elapsed time from gas exposure to sounding of the alarm. For replicates, the meters were placed in atmospheres with clean air for at least 10 minutes between each analysis. Additionally, visual inspection of the readout was performed prior to each trial to ensure that the monitor reading was at 0% O_2, 0% LEL CH_4 or 0 ppm H_2S.
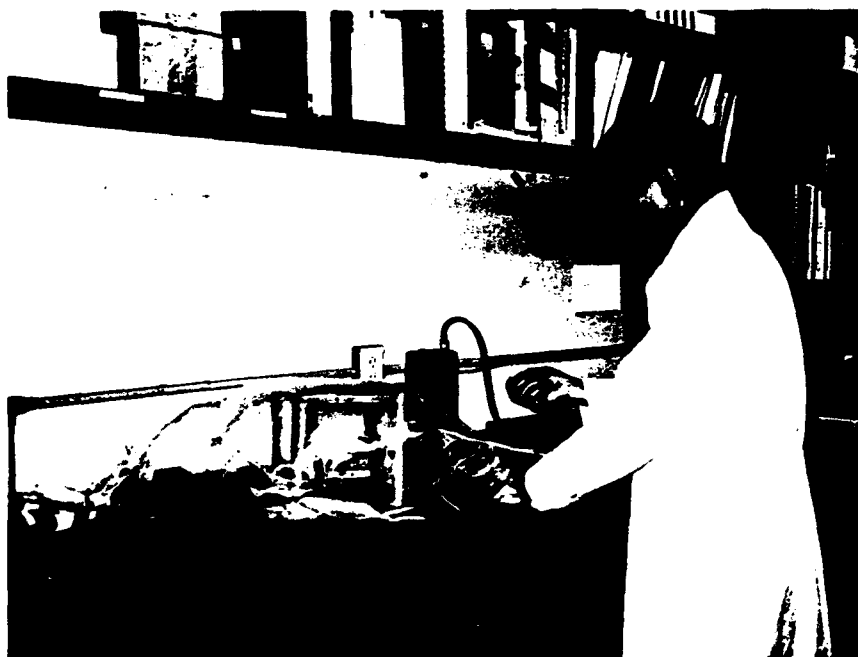
FIGURE 4.   Set-up for the determination of alarm response time. The "framework" of a
box similar to that shown in Fig. 3 was sealed inside a glove bag filled
with the test gas. The glove bag (part number X-17-17H, Instruments for
Research and Industry, Inc., Cheltenham, PA), smaller than that shown in
Fig. 2, has dimensions of 17" x 17" x 11" and only one equipment entry
sleeve. The gas meter located inside the bag was used to monitor the
concentration of test gas in the glove bag.

4. Remote Sampling Capability

Only two models were supplied equipped with built-in or internal, motorized sampling pumps, namely: G700, and Compur Tritox M. Only these two meters were evaluated using motorized pumps. It should be noted, however, that external motorized pumps can be purchased separately for all the monitors used in the study. Hence, all of the instruments evaluated can be used for confined space applications. The major difference between the two pumps installed in both systems is that the motorized pump for the Compur Tritox M was always running whenever the meter was on, while the G700 had a pump that can be turned on by the user when desired. Therefore, the G700 can function in both the pump mode and diffusion mode. The pump of the G700 meter runs for only 20 seconds at a time. After 20 seconds the pump automatically turns off and has to be restarted by the user.

For the other monitors; namely the PhD, CGM929A, HMX271 and MiniGas; remote sampling capability was evaluated using a manual pump (more specifically, a rubber bulb aspirator) as illustrated in Fig. 5. Evaluation of the remote sampling capabilities of the other monitors (i.e., models CGS-80, CGS-90, Compur Tritox D and S108) were not performed since no calibration cup, sensor compartment cover or sample draw cover was supplied for these meters. The PhD and MiniGas monitors included a manual pump for remote monitoring.

The set-up used for evaluating the remote sensing capability of the different meters is illustrated in Fig. 6. A glove bag filled with the test mixture was connected to the gas monitor by rubber tubing. To monitor the test gas concentration inside the bag, one of the meters was placed inside the bag for the duration of the experiment. The test gases used consisted of 16 and 25% O_2 in N_2, 30% LEL CH_4 in air, and 35 ppm H_2S in air. Pertinent data recorded included steady-state concentration of target gas, time required to reach the steady-state value, and alarm response time. Alarm response time was determined as the elapsed time from turning the pump on to sounding of the alarm. Finally, for the Compur Tritox M, a 1.98 m tubing with an internal diameter (i.d.) of 4 mm was supplied and used for the experiment as shown in Fig. 6. No tubing was provided for the G700 meter, hence, a 1.83 m with an i.d. of 4.8 mm (or 3/16 inch) Tygon tubing was used instead. For the performance of manually operated pumps, the tubing provided for the PhD monitor which was 1.50 m long with an i.d. of 4.8 mm was used for all the monitors. For the latter case, the bulb was located 152.4 mm from the sample draw cover.

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Additional data were collected for the MiniGas using the manufacturer supplied tubing-aspirator assembly which consisted of a 3.18 m tubing with an i.d. of 6 mm with the aspirator located 190.5 mm away from the sensor cover.

FIGURE 5.   PhD monitor with manual pump assembly. The pump is operated by squeezing the rubber bulb aspirator. Note the original sensor compartment cover used for the diffusion mode on the left side of the picture

FIGURE 6.   Set-up for evaluation of remote sensing capability. The glove bag used
             was similar to that shown in Fig. 4. The gas meter located inside the bag
             was used to monitor the concentration of test gas in the glove bag.

D. Evaluation of Operational Parameters and Other Physical Characteristics and Value Added Features

1. "Memory" for NiCd-Powered Monitors

The "memory" of NiCd rechargeable batteries refers to the widely held impression that NiCd batteries repeatedly discharged to a particular state (e.g., 50% of full charge) will eventually be "conditioned" to provide only that amount of service before needing to be recharged. In other words, if the battery is not fully discharged between chargings then the amp-hour capacity will decrease for successive charges. That this is a widely held notion is illustrated by recommendations in operator manuals of some NiCd powered equipment that the batteries occasionally be completely discharged (c.f., Operating Instructions Universal Flow Sample Pump, Model 224-43XR, SKC, Inc.) in order to avoid the memory effect. On the other hand, according to Gates Energy Products,[23] "memory" in NiCd batteries is a misconception and does not exist. If memory in NiCd batteries is a myth, then a principle disadvantage of these rechargeable batteries disappears. The choice between using rechargeable NiCd's or disposable alkaline cells in portable monitors is thus profoundly affected by the question of whether or not the memory effect exists. Consequently, the possible manifestation of any memory effect in the NiCd powered monitors in this study (all monitors except the CGM929A, HMX271, and MiniGas monitors) was investigated.

The protocol used involved periodic cycling of the discharging-charging process; the monitor was used for three hours per day (i.e., left "ON" in "clean" laboratory air) followed by overnight recharging (for sixteen hours). For each cycle the instrument was turned "ON" and placed on a benchtop in clean lab air for three hours per day, from 12:30 PM to 3:30 PM. The instruments were then recharged from 4:30 PM to 8:30 AM the next day. The instrument was "OFF" during other times of the day. After ten cycles, the time required to fully discharge the battery was measured, together with the voltage of the battery during different stages of the discharge. The low battery or battery failure alarm, as detected by the monitor, was used as basis for determining when the battery is no longer capable of supplying sufficient power for proper monitor operation (or when the battery is "fully" discharged).

2. Portability

The portability of the gas meters was determined by measuring both the physical dimensions (i.e., length, width and height) and weight of each instrument. A conventional desk ruler was used to determine the dimensions of the monitor, while the mass of the

"bare" monitor (i.e., without the carrying case but including the power source) was determined using a Mettler PE 3600 Delta Range balance.

3. Ease of Operation and Maintenance

This part of the study included a subjective appraisal of the following: ease or complexity of monitor operation, and comprehension of the manufacturer-supplied instruction manual; ease of servicing and maintenance; access to and reliability of the manufacturer's service/technical support department; and, availability of instrument parts. Subjective evaluation of some of the latter operational characteristics and value added features was based on parameters such as: response from untrained individuals upon reading the manuals; turn-around time for monitor repair; time for shipment of parts; and, reputation of the manufacturer and length of time in business.

4. Cost

Data used in this section were obtained from information supplied by the monitor manufacturers and distributors, and the U.S. Coast Guard Research and Development Center. It is emphasized that as indicated earlier in the text, the different gas monitors evaluated in the study were selected and purchased by the U.S. Coast Guard.

III. <u>RESULTS AND DISCUSSION</u>

B. Evaluation of Detection Capability

1. Accuracy of Sensor Response

a. Oxygen Sensor

The four standard oxygen mixtures used contained 16.08, 19.58, 21.19, and 25.45% oxygen by volume in nitrogen. The oxygen sensor readings for the four mixtures are given in Table 3. For each monitor, three sets of data are listed corresponding to replicate measurements collected approximately one month apart. As can be seen from Table 3, very good reproducibility was obtained for each data set. For models tested in duplicate (i.e., for the PhD, CGM929A, G700 and S108; including the HMX271 and MiniGas), reproducibility for the two data sets (i.e., with each set consisting of three readings obtained approximately one month apart for the same meter) is also very good, with the largest range being equal to only 0.6% oxygen. Most pairs, however, differed only within the range of 0.0 to 0.2%. The accuracy and precision of all the results (i.e., for all the instruments) were also very good with the following ranges being observed for each of the

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standard mixtures: 15.1 to 16.4 for 16.08% oxygen, 18.7 to 20.0 for 19.58% oxygen, 20.5 to 21.5 for 21.19% oxygen, and 24.2 to 25.2 for 25.45% oxygen.

The correlation slopes for the data in Table 3 are shown in Table 4. Correlation slopes of 1.0 indicate that the monitor readout tracks the gas concentration with perfect accuracy during calibration. All of the monitors yielded correlation slopes within reasonable experimental variation. The Scott S108 monitor gave the lowest correlation slope during calibration, and even that only worst case was only slightly beyond the 95% confidence limits. The accuracy of the responses for the different monitors were compared by using the correlation data to estimate the measurement error at the critical points of 19% O_2 and 23% O_2. All of the monitors responded were accurate at the critical levels to within experimental variance. Figure 7 illustrates the comparison of correlation slopes and response accuracy at the critical points. Again, none of the monitors was particularly superior or inferior to the others in terms of O_2 response.

Table 3.   Response to different oxygen concentrations. [a,b,c]

Oxygen concentration:	16.08%		19.58%		21.19%		25.45%	
Model SN	reading	S	reading	S	reading	S	reading	S
PhD (DK108-1428)	15.3	0.36	19.0	0.18	20.7	0.00	25.1	0.27
PhD (DK108-1429)	15.3	0.36	19.0	0.18	20.7	0.09	25.1	0.27
CGM929A (4571)	15.9	0.27	19.0	0.27	20.9	0.00	24.7	0.22
CGM929A (4572)	16.2	0.32	19.2	0.22	20.9	0.00	24.3	0.27
CGS-80[e]	16.2	0.32	19.8	0.27	21.2	0.27	24.7	0.54
CGS-90	15.6	0.11	19.2	0.11	20.8	0.11	24.8	0.16
G700 (91090289)	15.8	0.11	19.2	0.11	20.8	0.05	24.5	0.22
G700 (91090290)	15.9	0.22	19.2	0.27	20.8	0.11	24.6	0.1
HMX271 (NiCd)	15.9	0.16	19.2	0.11	20.7	0.00	24.5	0.16
HMX271 (Dry Cell)	16.3	0.49	19.7	0.54	21.2	0.54	25.1	0.38
Compur Tritox D	16.0	0.32	19.2	0.22	20.7	0.11	24.3	0.22
Compur Tritox M	15.9	0.00	19.2	0.11	20.7	0.11	24.5	0.16
MiniGas (NiCd)	15.9	0.11	19.3	0.27	20.8	0.16	24.7	0.16
MiniGas (Dry Cell)	15.9	0.11	19.3	0.27	20.9	0.16	24.8	0.05
S108 (91361634)	15.9	0.16	19.2	0.05	20.7	0.11	24.4	0.27
S108 (91361656)	15.8	0.18	19.1	0.18	20.6	0.18	24.3	0.45

[a] Oxygen in dry nitrogen. Concentrations were certified by Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA using gas chromatography.

[b] The meters were set to read 20.9% v/v oxygen (i.e., "zeroed") in clean, ambient air.

[c] n=3 (except n=2 for PhD); replicates 1 month apart; S = standard deviation.

[d] The oxygen readout for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% oxygen increments.

Table 4. Relative accuracy and precision of oxygen meter response

| Model (SN) | Correlation[a] | | Error at alarm points | | msmt |
	Slope	SE[b]	low(19%)	high(23%)	S[b]
PhD (DK108-1428)	1.04	0.039	-0.6	-0.4	0.20
PhD (DK108-1429)	1.04	0.039	-0.6	-0.5	0.22
CGM929A (4571)	0.96	0.041	-0.4	-0.6	0.19
CGM929A (4572)	0.90	0.025	-0.3	-0.8	0.20
CGS-80	0.96	0.002	0.0	-0.2	0.35
CGS-90	1.00	0.016	-0.5	-0.5	0.12
HMX271 (NiCad)	0.93	0.032	-0.4	-0.7	0.11
HMX271 (Dry Cell)	0.93	0.025	-0.2	-0.5	0.49
G700 (91090289)	0.95	0.016	-0.4	-0.7	0.12
G700 (91090290)	0.95	0.022	-0.5	-0.7	0.19
Compur Tritox D	0.91	0.031	-0.5	-0.9	0.22
Compur Tritox M	0.93	0.003	-0.4	-0.7	0.09
MiniGas (NiCad)	0.95	0.021	-0.4	-0.6	0.18
MiniGas (Dry Cell)	0.96	0.006	-0.3	-0.5	0.15
S108 (9136134)	0.92	0.017	-0.4	-0.7	0.15
S108 (9136156)	0.92	0.026	-0.5	-0.9	0.24

[a] slope of 1.0 is ideal

[b] standard error of correlation slope, degrees of freedom (d.f.)=5, except for PhD units d.f.=3

c Values are units deviation (in $\%O_2$) in a reading from a gas sample with an O_2 concentration at the alarm setpoints shown above (19%).

b. Combustible Gas Sensor

Three methane mixtures— 5.1, 15.8, and 31.5% LEL methane in air— were used to test monitor response to combustible gases. Table 5 summarizes the results from triplicate tests, performed approximately one month apart with fresh calibrations. Table 6 provides correlation and accuracy information drawn from the data in Table 5. The individual meter readings in units of %LEL listed in Table 5 are an indication of how a particular instrument performed over a range of methane concentrations over a period of three months in terms of reproducibility and accuracy for that meter at that concentration of methane. In Table 6, we pooled ALL of the readings comprising the values in Table 5 in order to assess how a particular meter performed over an entire range of methane concentrations over time. Thus, from Table 5 one could conclude that the S108 (SN91361656) unit was inferior to the HMX271 or Compur Tritox D units because the standard deviations of the replicate readings at all three methane concentrations for the S108 unit were in the range of 0.5-4 %LEL units and thus it was less precise than the other units. However, Table 6 shows the S108 unit to be relatively accurate over the range tested though somewhat imprecise, whereas the HMX and Compur units were relatively precise but also relatively inaccurate. Further, Table 5 shows the HMX and CGM units to provide consistently low readings at lower methane concentrations. Clearly, these data should be used together to provide a full picture of instrument performance and in setting other parameters such as alarm points for combustible gases.

No data were obtained for the CGS-80 and CGS-90 monitors since the combustible gas readout for the CGS monitors consist of a segmented bar graph ranging from approximately 10 to 20% LEL (see Fig. 8). The combustible gas readout for the other monitors was in increments of 1% LEL Also, all the instruments use catalytic combustion sensors except the CGS-80 and CGS-90 which have MOS sensors. The limitations of both sensor types are discussed elsewhere.[1]

All of the monitors showed rather higher variances for combustible gas measurements than they did for oxygen measurements. Standard deviations *(abbreviated as S throughout this report)* for combustible gas readings ranged from slightly less than 1%LEL (methane) to a high of just over 3%LEL(methane) with a median of about 1%LEL (methane). The PHD and HMX271 units exhibited the lowest variability in combustible gas concentrations. The S108, MiniGas and the Compur M units showed the highest uncertainties.

The monitors also showed poorer accuracy for combustible gas than they did for oxygen. Figure 9 illustrates the pattern of correlations and errors associated with this set of monitors for combustible gases. Correlations slopes vary substantially for the different instruments, but because of the relatively high uncertainties in measurements the differences are only marginally significant. Units showing significant deviations from ideal correlation were the CGM929A (>1.0), the MiniGas units (<1.0) and the S108 units(<1.0).

More important than the correlation slopes is the bottom line: How accurately does the monitor report the concentration at critical concentrations of combustible gas? Table 6 contains the estimated errors at three different concentrations, 10%, 20%, and 30%LEL (methane). Most of the units showed a slight positive bias, readings higher than the actual concentration. These biases, while barely significant, err in the direction of safety. Higher readings will result in premature warnings rather than allowing workers to continue working in an unsafe environment. Again note that the size of the error for most of these instruments is small enough that false warnings will not be a problem in practice.

Of more concern was the clearly significant tendency of the HMX271 models to report low concentrations for combustible gas. The HMX showed a relatively high negative bias. That is, the units tended to under-report combustible gas concentrations. This increases the possibility of allowing workers to continue in an unsafe environment. The negative bias is more significant considering that most gases, such as pentane, tend to yield lower readings than methane anyway (c.f., Figure 12). The bias in the HMX271 response could easily be compensated by safety margins that should be incorporated into operational procedures.

The PHD units showed clearly superior performance for combustible gas in both precision and accuracy. Among the instruments tested, these units had the among lowest standard deviations and virtually no error at the critical concentrations. Furthermore, the PHD units showed the highest consistency between copies of the same model. The G700 models were also accurate and without large differences between between the duplicate units. While the precision of the combustible gas readings was not exceptional for the G700's, their standard deviation of 1-2% puts them in the middle of the precision range observed for the models tested.
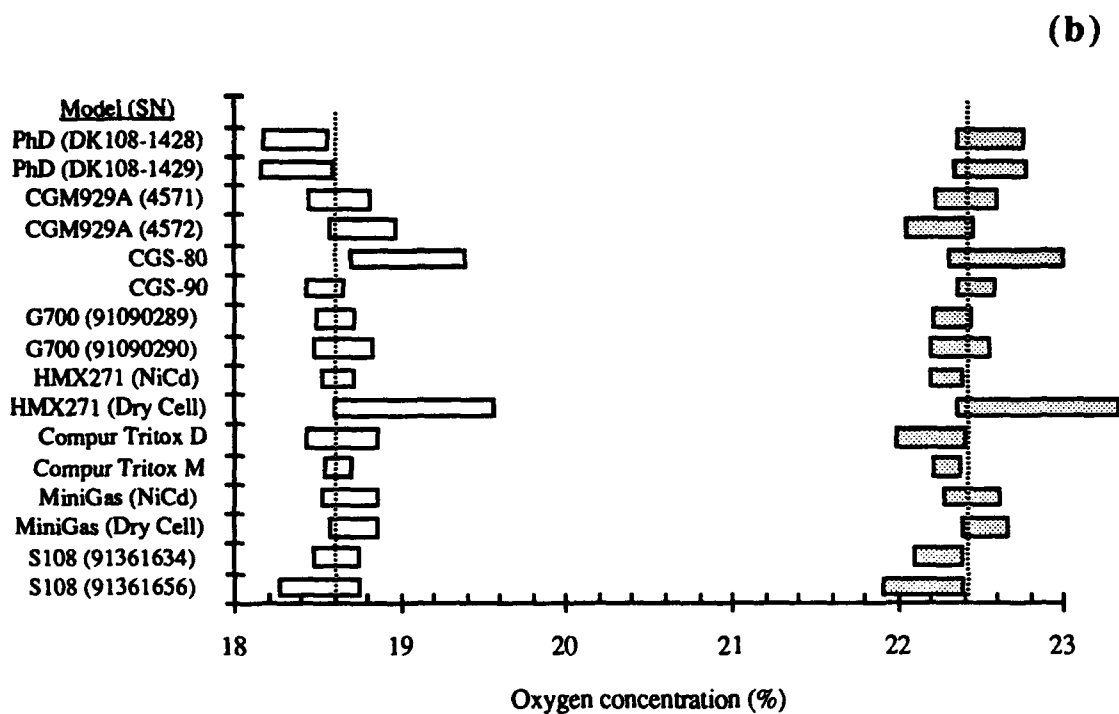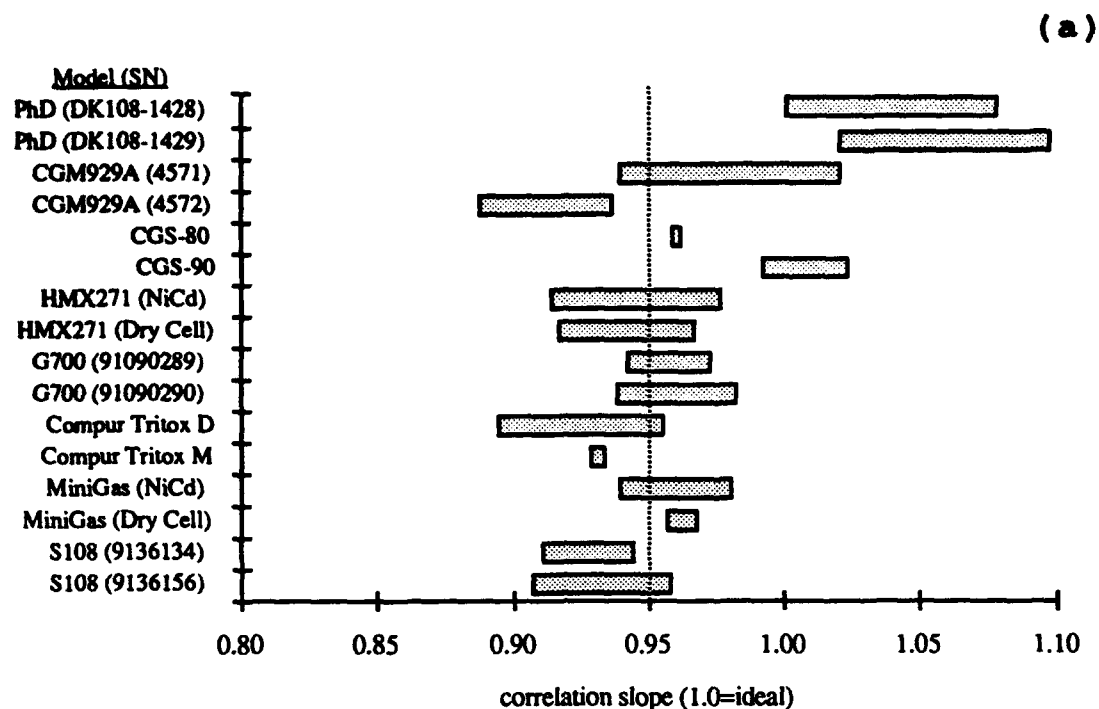
FIGURE 7.   Response characteristics of O_2 monitors: (a) correlation between
instrument reading and O_2 concentration, ideal=1.0; (b) readings at lower
alarm point (19% O_2) and upper alarm points (23% O_2). Broken lines
represent median values. Bars represent ±1S range.

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Table 5. Response to different methane concentrations[a].

Model SN	5.1% LEL Methane reading	5.1% LEL Methane S[b]	15.8% LEL Methane reading	15.8% LEL Methane S	31.5% LEL Methane reading	31.5% LEL Methane S
PhD (DK108-1428)	5.7	0.54	16.0	1.08	31.0	1.08
PhD (DK108-1429)	4.7	0.54	15.3	0.54	30.0	1.08
CGM929A (4571)	1.0	0.00	18.0	0.00	35.0	1.78
CGM929A (4572)	3.3	1.08	22.7	1.62	45.0	1.62
CGS-80[c]						
CGS-90[c]						
G700 (91090289)	5.3	2.16	16.3	1.62	30.7	2.16
G700 (91090290)	6.3	0.54	17.3	0.54	30.7	2.16
HMX271 (NiCd)	2.3	0.54	13.7	0.54	29.7	0.54
HMX271 (Dry Cell)	2.7	0.54	13.3	0.54	29.0	1.08
Compur Tritox D	6.0	0.00	18.5	0.54	35.5	0.54
Compur Tritox M	6.7	0.54	18.0	2.70	34.7	4.86
MiniGas (NiCd)	6.3	0.54	17.5	2.67	29.7	2.16
MiniGas (Dry Cell)	9.3	2.16	19.5	4.45	29.0	4.32
S108 (91361634)	5.0	2.16	12.7	1.62	24.0	3.78
S108 (91361656)	5.3	0.54	14.0	2.70	27.7	4.32
Median	5.3	0.54	16.8	1.35	30.3	1.97

[a] Methane in air. Concentrations were certified by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] n=3 for all, except n=2 for CGM929A (4571). Replicate analyses were performed, with fresh calibrations, approximately one month apart.

[c] No values were obtained for the CGS-80 and CGS-90 because the display consisted of a nonlinear bar graph ranging only from approximately 10% to 20% LEL.

Table 6. **Relative accuracy and precision of combustible gas meters**[a]

| Model SN | Correlation | | Error at alarm points (%LEL) | | measurement |
	Slope	SE	10%	20%	S
PhD (DK108-1428)	0.96	0.011	0.4	0.0	0.90
PhD (DK108-1429)	0.96	0.012	-0.5	-0.9	0.72
CGM929A (4571)	1.27	0.050	-1.5	1.2	0.59
CGM929A (4572)	1.57	0.036	2.0	7.6	1.44
CGS-80[b]					
CGS-90[b]					
G700 (91090289)	0.96	0.084	0.3	-0.1	1.98
G700 (91090290)	0.92	0.050	1.3	0.4	1.08
HMX271 (NiCd)	1.03	0.011	-2.5	-2.2	0.54
HMX271 (Dry Cell)	1.00	0.036	-2.4	-2.5	0.72
Compur Tritox D	1.11	0.013	1.7	2.8	0.36
Compur Tritox M	1.06	0.093	1.9	2.5	2.70
MiniGas (NiCd)	0.88	0.034	1.0	-0.2	1.79
MiniGas (Dry Cell)	0.74	0.050	3.4	0.8	3.06
S108 (91361634)	0.72	0.126	-1.5	-4.3	2.52
S108 (91361656)	0.93	0.042	0.1	-0.6	2.52
Median	0.96		0.2	-0.2	0.99

[a] n=3 for all, except n=2 for CGM929A (4571). Replicate analyses were performed, with fresh calibrations, approximately one month apart.

[b] No values were obtained for the CGS-80 and CGS-90 because the display consisted of a nonlinear bar graph ranging only from approximately 10 to 20% LEL.

[c] standard error of correlation slope, degrees of freedom (d.f.)=5, except for PhD units d.f.=3

GAS

O₂

10   20

17   19   21   23   25

TOXIC

10   PPM   20

10   % LEL   20

COMB
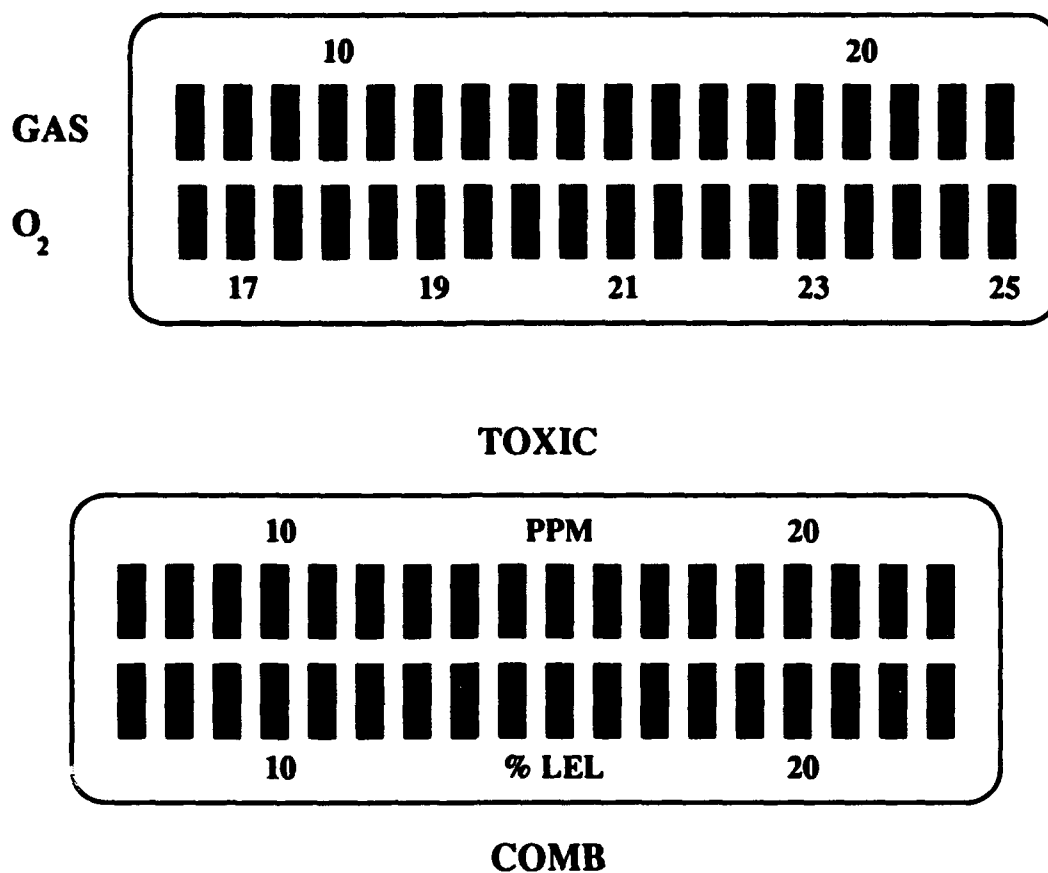
FIGURE 8.   Liquid crystal display for the CGS-80 [Top] and CGS-90 [Bottom] illustrating the eleven segment bar graph from approximately 10 to 20 ppm H_2S or % LEL. Note that the GAS scale for the CGS-80 [Top Diagram] indicates either the approximate concentration of H_2S or CH_4 depending on the mode selected by the user. It should be noted that a separate digital % O_2 display is available for the CGS-90.

(a)

(b)
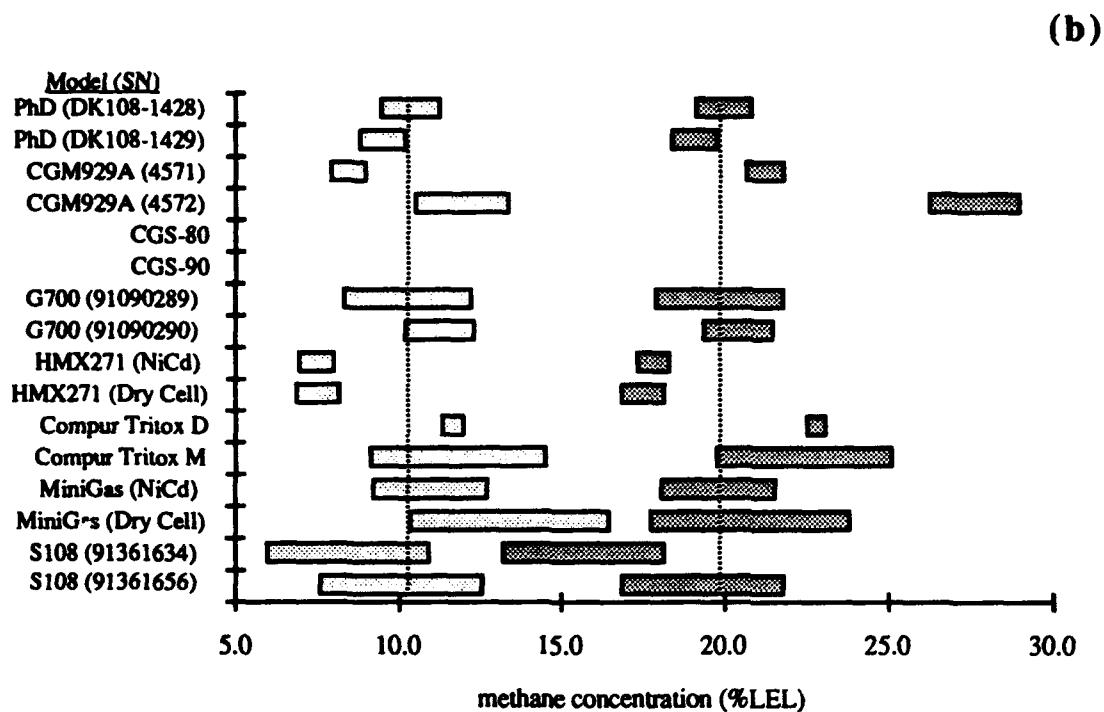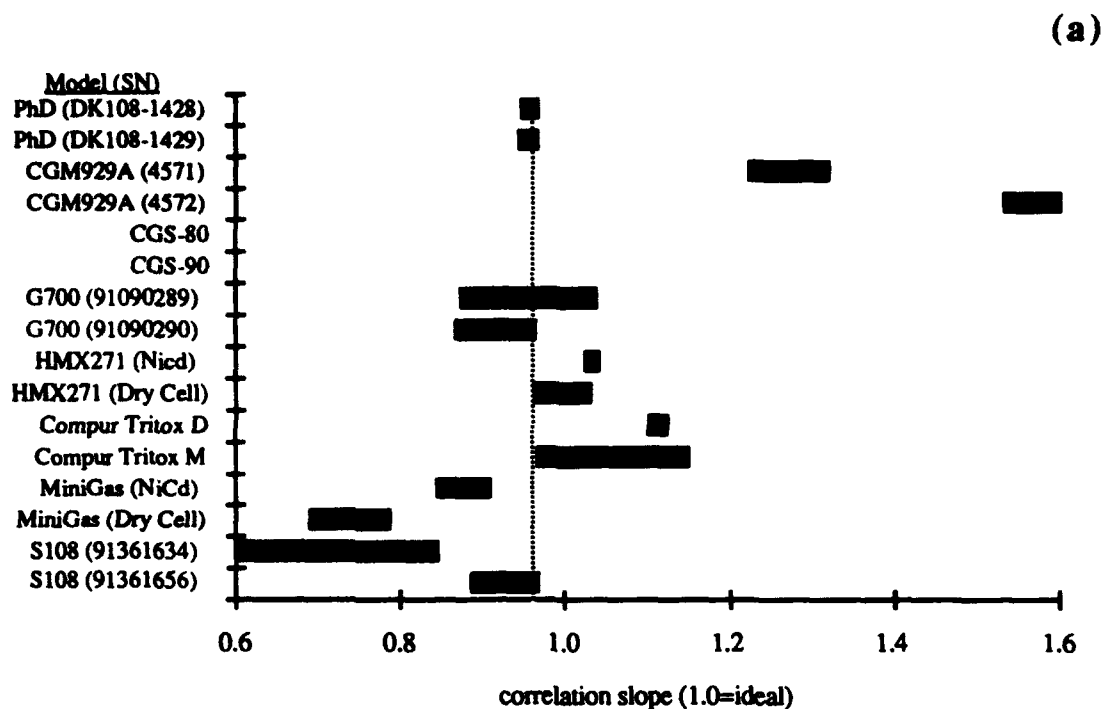
FIGURE 9.   Response characteristics of combustible gas monitors: (a) correlation
between instrument reading and methane concentration, ideal = 1.0; (b)
readings at two alarm points (10% LEL and 20% LEL). Broken lines
represent median results. Bars represent ±1S range.

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c. Toxic Gas Sensor

The three hydrogen sulfide (H_2S) mixtures used to test the toxic gas sensor response were 6.5, 18.1 and 35.1 ppm H_2S. As for the combustible gas sensor results, no accuracy data were obtained for the CGS-80 and CGS-90 monitors since the toxic gas readout for these meters also consist of an segmented nonlinear bar graphs ranging from approximately 10 to 20 ppm H_2S (Figure 8). The toxic gas readout for the other monitors was in increments of 1 ppm H_2S. Finally, all the instruments investigated are equipped with electrochemical toxic gas sensors except the CGS-80 and CGS-90 which have MOS sensors.

The monitor results observed for these H_2S mixtures are shown in Table 7. Precision of the H_2S readings was the poorest of the three sensors for all monitors, being slightly worse than the combustible gas modules. The standard deviations ranged from 1.5 to almost 10 ppm although standard deviations of 2.5 to 3.0 ppm were more typical. The 1.5 ppm lower limit on standard deviations is reasonable given that the readings are in increments of 1 ppm. The HMX271, MiniGas units showed strong correlations between variance and concentration of H_2S. The S108 also showed a correlation, though much more weakly. At the lower concentration the uncertainties for these units were comparable to the other units. At higher concentrations, however, the uncertainties were higher by a factor of 2 to 4. Other than this correlation, no significant differences in the precision of results appeared among the various models tested.

Correlation slopes were substantially below 1.0 for all of the instruments except the Compur models and, again except for the Compur models, no significant difference was apparent between any of the units. Unlike the results for the combustible gases, however, the low correlations translated directly into low readings for H_2S. All of the units, except the Compur units, reported low values for H_2S. The variance and error in the readings for the Compur models were so high that the values must be considered meaningless. At levels of 10 ppm H_2S (the 8 hr-TWA level) all of the units showed a negative bias of 2 to 3 ppm H_2S. Because of the high standard deviations in the measurements, though, such a bias is only marginally significant. The MiniGas monitors seemed slightly more accurate than the other models for H_2S, but again the high uncertainties minimized the significance of the difference. At 18 ppm H_2S most of the monitors showed a negative bias of 4-5 ppm. The difference between the accuracy of the MiniGas and the other monitors showed up more strongly at the higher concentration of H_2S.

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The tendency of all of these units to underestimate H_2S concentration is an important operational consideration. Care should be taken that workers are not exposed to excess concentrations of H_2S as a result of inaccurate measurements. The OSHA ceiling value for H_2S is only 15 ppm. The uncertainty and bias in the measurements nearly obliterates the difference between the TWA value of 10 ppm and the ceiling value of 15 ppm. Workers tend to become inured to the odor associated with these levels of H_2S so that accurate instrumental detection is important even for a pungent gas such as H_2S.

The Compur units showed H_2S levels above the ceiling value for all of the H_2S test gases. In practice such responses would quickly become useless for ensuring worker safety as workers would tend to ignore or defeat warning associated with these false indications of hazard. It is possible that these units were malfunctioning during the test as we can see no use for an instruments that provides such grossly inaccurate results. The failure of the combustible gas sensor did prevent the entire set of H_2S experiments from being performed with the Compur units.

The response of the CGS units (which use MOS sensors) also poses a serious concern. These units use segmented bar graphs to display toxic gas concentrations, possibly to address nonlinear response characteristics. The concern with the CGS units is the unreliability of their ability to detect hazardous levels of H_2S. The bar graph readings were converted to numerical values in Table 9. The CGS units both reported undetectable levels of H_2S in the 18 ppm H_2S test gas. This level is above the OSHA ceiling and clearly the unit should report at least a detectable level of H_2S. At the 35 ppm level both units did report the presence of H_2S; the CGS-80 unit reported the level to be 19 ppm and the CGS-90 unit reported only ">23 ppm". Such gross underreporting of H_2S concentrations significantly enhances the possibility of exposing workers to unsafe conditions. While these units might be useful for detection of serious, immediately life threatening, concentrations of H_2S during an emergency this type of performance is not useful for safety monitoring in the context of chronic exposures to low levels of the gas.

Table 7 Response to different H$_2$S concentrations

Model (SN)	6.5 ppm H$_2$S[a] reading[b]	S	18.1 ppm H$_2$S reading[c]	S	35.1 ppm H$_2$S reading[c]	S
PhD (DK108-1428)	5.7	1.5	12.7	1.6	24.7	2.2
PhD (DK108-1429)	5.3	1.6	12.7	1.6	25.0	3.2
CGM929A (4571)	7.0	2.2	13.3	2.7	25.0	3.2
CGM929A (4572)	6.0	1.8	13.0	1.6	25.0	1.6
CGS-80[d]						
CGS-90[d]						
G700 (91090289)	5.7	2.7	12.7	1.6	27.0	1.6
G700 (91090290)	6.0	2.7	13.3	2.7	27.3	3.2
HMX271 (NiCd)	5.3	2.7	14.0	4.9	28.3	8.1
HMX271 (Dry Cell)	5.0	2.7	14.0	4.9	28.0	8.1
Compur Tritox D	18.0		33.0		48.0	
Compur Tritox M	21.0		38.0		72.0	
MiniGas (NiCd)	7.7	2.7	14.3	4.9	28.0	9.7
MiniGas (Dry Cell)	9.3	3.8	16.0	3.2	30.0	6.5
S108 (91361656)	3.7	2.7	14.7	2.7	27.3	7.6
S108 (91361656)	4.7	2.2	13.7	3.2	27.3	3.8
median	5.8		13.8		27.3	

[a] Hydrogen sulfide in air. Concentrations were certified by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] n=3 except n=2 for Compur Tritox D, Compur Tritox M, CGM929A (both units). Replicates performed approximately one month apart

[c] n=3 except n=2 for Compur Tritox D and Compur Tritox M

[d] No values were obtained for the CGS-80 and CGS-90 because the display consisted of a nonlinear bar graph ranging only from approximately 10 to 20 ppm hydrogen sulfide..

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Table 8. Relative accuracy and precision of toxic gas meter response[a].

Model (SN)	correlation[b]		Error at alarm points		msmt.
	slope	SE	10.0%	18.0%	S
PhD (DK108-1428)	0.67	0.020	-2.3	-4.9	1.8
PhD (DK108-1429)	0.69	0.044	-2.5	-5.0	2.2
CGM929A (4571)	0.67	0.082	-1.9	-4.6	2.7
CGM929A (4572)	0.71	0.060	-2.7	-5.1	1.7
CGS-80[d]					
CGS-90[d]					
G700 (91090289)	0.75	0.028	-2.3	-4.3	2.0
G700 (91090290)	0.75	0.040	-1.9	-3.9	2.9
HMX271 (NiCd)	0.81	0.118	-2.1	-3.6	5.2
HMX271 (Dry Cell)	0.81	0.119	-2.3	-3.9	5.2
Compur Tritox D	1.04	0.000	12.7	13.0	9.7
Compur Tritox M	1.80	0.000	15.9	22.2	9.7
MiniGas (NiCd)	0.72	0.174	-0.4	-2.7	5.8
MiniGas (Dry Cell)	0.73	0.119	1.2	-0.9	4.5
S108 (91361656)	0.82	0.103	-2.9	-4.3	4.3
S108 (91361656)	0.79	0.032	-2.6	-4.3	3.1
Median	0.75		-2.2	-4.1	3.7

[a] Hydrogen sulfide in air. Concentrations were certified by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] n=3 except n=2 for Compur Tritox D, Compur Tritox M. Replicates performed approximately one month apart

[c] n=7 except n=5 for CGM929A units and n=3 for Compur units.

[d] No values were obtained for the CGS-80 and CGS-90 because the display consisted of a nonlinear bar graph ranging only from approximately 10 to 20 ppm hydrogen sulfide

2. Sensor Selectivity

a. Toxic Gas Sensor

Electrochemical toxic gas cells are known for their specificity, accuracy and linear response. MOS-based toxic gas sensors, on the other hand, are much maligned and considered troublesome to use because of their inherent nonlinear response, nonspecificity, and loss of sensitivity during prolonged exposure to fresh air.[1, 12, 19, 21, 22, 24-28] According to the proponents of the MOS sensor, however, the nonspecificity of the MOS as toxic gas detector can be used as an advantage since "it responds to an almost infinite number of toxic gas molecules with a sloppy but usable correlation of response to toxicity," especially with the incorporation of microprocessor control in state-of-the-art meters.[12, 22, 29] The resurgence of the MOS sensor in recent years reflects the trend toward more emphasis on protection rather than discrimination for use of personal monitors.

From Table 9 it can be seen that only the toxic electrochemical cells of the PhD and HMX271 showed no response to CO as evidenced from the 0 ppm H_2S readings for these meters using the 50 ppm CO mixture. The other four monitors investigated with H_2S electrochemical cells reacted

The selectivity of both toxic sensor types were determined using H_2S, CO and CH_4 mixtures in air. The readings observed for these gases are listed in Table 9. As can be seen, the results for the 18 and 35 ppm H_2S mixtures are comparable to those in Table 7. For example, using 18 ppm H_2S as test gas, the toxic sensor response in Table 9 for the PhD SN DK108-1428 meter was 12 ppm H_2S while similar values in Table 7 were 14, 11 and 13 ppm H_2S.to 50 ppm CO according to the following trend: for the CGM929A, the electrochemical cell responds to H_2S 3.6 times greater than CO; for the G700, the electrochemical cell responds to H_2S 4.2 times greater than CO; for the S108, the electrochemical cell responds to H_2S 10 times greater than CO; and, for the MiniGas, the electrochemical cell responds to H_2S 20 times greater than CO. Hence, the response of the toxic electrochemical sensor to CO is relatively low for the MiniGas and S108 meters. It should be noted that the relatively higher response of the CGM929A H_2S cell to CO was expected since as stated in the instruction manual that came with the instrument, the toxic cell "responds to H_2S 3.4 times greater than CO," which was very close to the experimentally observed value of 3.6.[30] Similarly, the response of the G700 H_2S sensor was also expected since as indicated in the instruction manual of the G700, cross sensitivities are expected for the cell with ethylene, carbon monoxide and hydrogen gases.[31] Finally, no definite trends can be stated regarding the specificity or selectivity of

MOS toxic gas sensor in personal monitors since as can be seen from the results for the CGS-80 and CGS-90, the MOS sensor of the CGS-80 responded more to 50 ppm CO than to 35 ppm H_2S, but no response was observed for the 50 ppm CO mixture for the CGS-90.

(a)

(b)
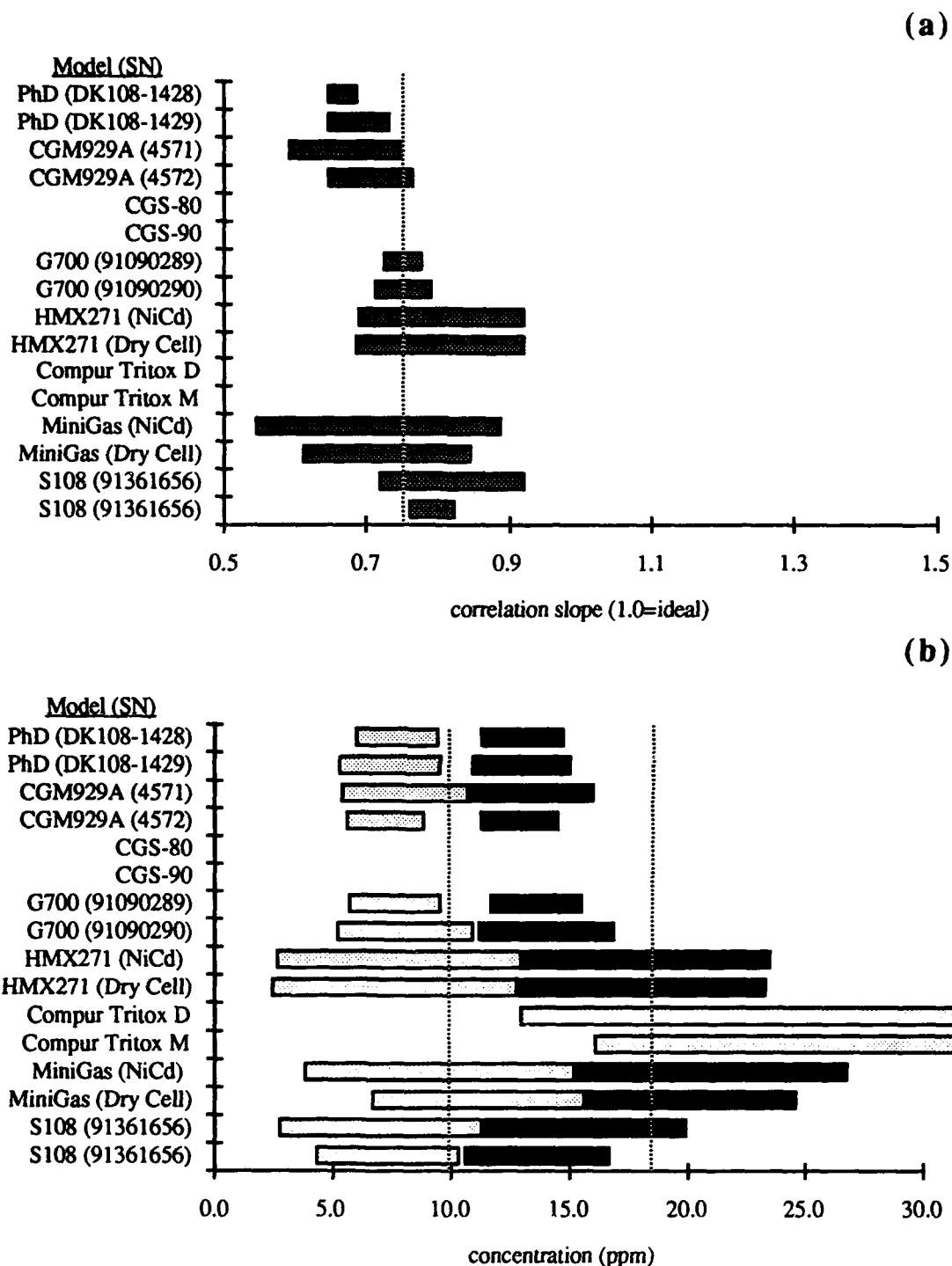
FIGURE 10.   Response characteristics of toxic gas monitors to H_2S: **(a)** correlation
between instrument reading and H_2S concentration, ideal=1.0; **(b)**
readings at two potential alarm points (10% and 18%). Broken lines
represent median values. Bars represent ±1S range.

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Table 9. Comparison between the selectivity of the electrochemical cell and the MOS sensor as toxic gas sensors. [a]

| | Response, as ppm H_2S to: | | | | | | | | Response Relative to H_2S | |
| | 18 ppm H_2S | | 35 ppm H_2S | | 50 ppm CO | | 30% LEL CH_4 | | CO | CH_4 |
Model (SN)	ppm	S	ppm	S	ppm	S	ppm	S		
PhD (DK108-1428)	12	1.0	21	1.2	0	0.0	0	0.0	0.0	0
PhD (DK108-1429)[b]	—		—		—		—			
CGM929A (4571)	13	0.6	26	0.6	14	1.0	0	0.0	0.4	0
CGM929A (4572)	13	0.0	24	0.6	14	1.0	0	0.0	0.4	0
CGS-80 [c]	ND		19		≥ 23		ND			
CGS-90 [c]	ND		≥ 23		ND		ND			
G700 (91090289)	12	0.6	21	1.2	12	0.0	0	0.0	0.4	0
G700 (91090290)	13	0.0	21	1.2	12	0.0	0	0.0	0.4	0
HMX271 (NiCd)	12	1.5	20	0.0	0	0.0	0	0.0	0.0	0
HMX271 (Dry Cell)	12		20	0.6	0	0.0	0	0.0	0.0	0
Compur Tritox D [d]	—		—		—		—			
Compur Tritox M [d]	—		—		—		—			
MiniGas (NiCd)	12	0.0	21	1.2	2	0.0	0	0.0	0.1	0
MiniGas (Dry Cell)	14	1.0	25	2.3	3	0.6	0	0.0	0.1	0
S108 (91361634)	12	1.2	20	0.6	5	0.0	0	0.0	0.2	0
S108 (91361656)	13	1.2	22	0.6	5	0.6	0	0.0	0.2	0

[a] Both sensor types were span calibrated using 18 ppm H_2S, except the CGM929A meters which were calibrated using 200 ppm CO but programmed to respond to ppm H_2S.

[b] instrument failure

[c] The display for both MOS sensor readings for the CGS-80 and CGS-90 are nonlinear bar graphs Thus an entry of "None Detected" can mean that the target gas concentration in the sample was less than the minimum limit of the display (< 10 ppm).

[d] No selectivity data were obtained for the Compur Tritox D and Compur Tritox M since both meters could not be operated due to the failure of the CH_4 sensors.

Finally, no cross sensitivity to methane was observed for toxic gas electrochemical sensors studied to 30% LEL CH_4. Similar results may also have been observed for both CGS meters with MOS sensors. Note, however, that an entry of "None Detected" in Table 9 may mean only that response by the MOS was less than the minimum limit of the display (see Fig. 8).

b. Combustible Gas Sensor

The two types of sensors commonly used for the detection of combustible gases in personal monitors are the catalytic combustion and MOS sensors. The catalytic combustion type is, however, more commonly employed because of its simplicity of detection and linear response up to at least 100% LEL of combustible gas.[1] Note, however, that since detection for the catalytic sensor depends on the quantitative measurement of the heat evolved when the gas is burned, the sensor cannot detect combustible gases in the absence of oxygen. The minimum required concentration of oxygen is about 16%.[21]

The measure of combustible gas differs from the measure of oxygen and H_2S in that rather than being a specific compound the analyte is a class of compounds– namely, combustible gases. Combustible gas monitors measure the presence of a combustible gas in terms of how close it is to the lower explosion limit, the lowest concentration at which it will support combustion. Usually the monitors are calibrated with a specific gas of known concentration. For the sake of convenience, the calibration gas may not be the one actually present in the atmosphere to be tested. Questions thus arise about how different members of the class of combustible compounds respond to the detection system. In other words, does it matter in the end whether the combustible gas is methane or hydrogen?

Thus two aspects of the sensor response were addressed under the rubric of selectivity: the effect of oxygen deficiency on response to combustible gas and the relationship between "combustible gas" response and the identity of the gas. Additionally for MOS sensors, which do not explicitly rely on combustion in the detection process, the effect of other noncombustible gases may be significant, though this effect was not studied here.

To monitor the effect of oxygen concentration on sensor response, three methane mixtures (having approximately 30% LEL CH_4) were employed containing 21, 19.5 and 0% O_2. The effect of oxygen on the catalytic combustion sensor response for the test mixtures containing approximately 30% LEL CH_4 can be seen in Fig. 11. No data were reported for the MiniGas Dry Cell, Compur Tritox D and Compur Tritox M since these

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monitors could not be operated properly during that period. As can be seen from Fig. 11, no significant differences were found in the results for CH_4 in air and CH_4 in oxygen deficient air (19.5% O_2). As expected, erroneously low % LEL CH_4 readouts were obtained for CH_4 in the absence of air for all of the meters using catalytic combustion sensors. For example, the HMX271 Dry Cell (in air containing 20.9% O_2 and 19.5% O_2) correctly reported 23% LEL CH_4. In the absence of oxygen (0% O_2), however, the HMX271 Dry Cell reported only 1% LEL CH_4 for the same 31% LEL CH_4 in N_2. That is why for pre-entry evaluation of the confined space air quality using personal monitors, the accepted protocol is to first determine the oxygen concentration of the atmosphere before taking the combustible gas reading. If the % O_2 detected is $\leq$ 16%, then the concentration of combustible gas as determined by the monitor will be erroneously low. Consequently, reading for any combustible gas in low oxygen (<16%) environments should be considered dangerous.
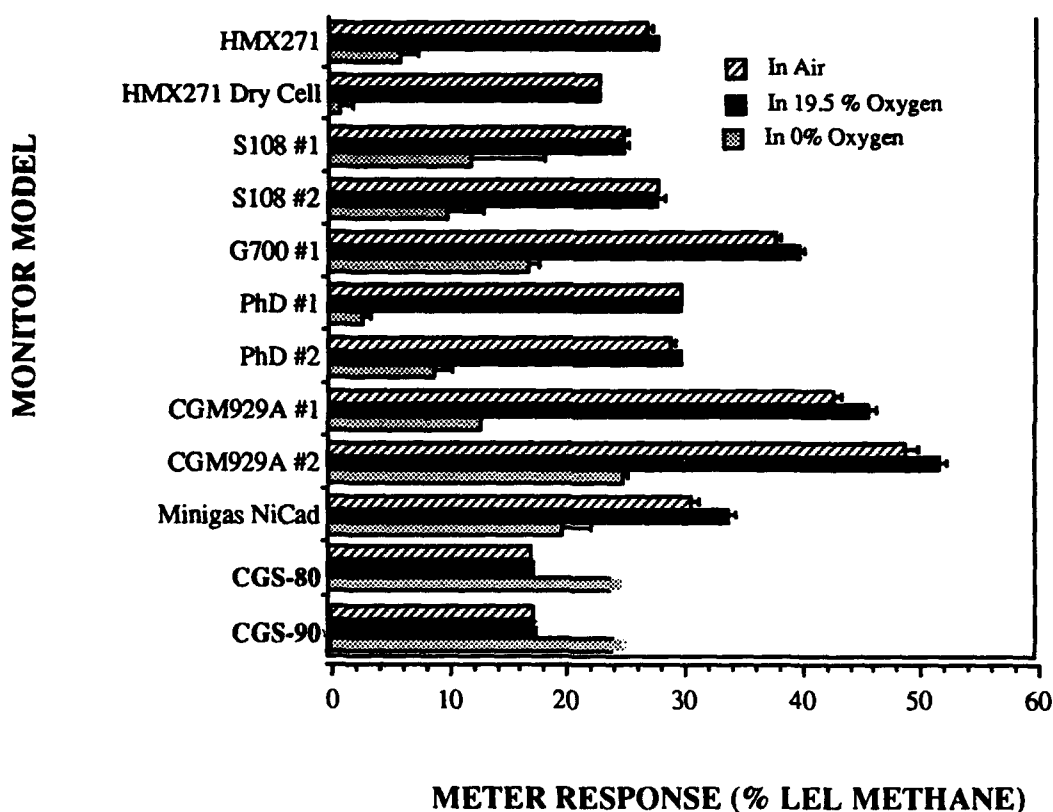
FIGURE 11   Effect of oxygen concentration on the catalytic combustion sensor response for test mixtures containing approximately 30% LEL methane.

One possible advantage of using MOS as combustible gas detector is its ability to detect flammable gases even at low O_2 concentrations. This property of MOS sensors was shown in the study and is summarized in Table 10. As can be seen, both MOS sensors for the CGS-80 and CGS-90 responded to 30% LEL CH_4 in air, and 31% LEL CH_4 in 19.5% O_2 and 0% O_2. Finally, it should also be noted that although the MOS sensors of the CGS meters were calibrated using 30% LEL CH_4 in air, the monitor displays were set at 20% LEL using the standard gas so that all meters, including those with upper readings of less than 30%, could be compared.

Both catalytic combustion and MOS as flammable gas detectors are nonspecific;[1] both sensor types would respond to any combustible gas present in the atmospheric air. They are calibrated to respond to a particular combustible gas, however, and have slightly different responses to different combustible gases. To evaluate the relative response of these sensors to different combustible gases, their response to 30% LEL methane in air was compared to that for 30% LEL pentane in air. A summary of the results obtained can be seen in Fig. 12 for meters with catalytic combustion sensors, and Table 10 for the CGS-80 and CGS-90 both with MOS sensors. It should be noted that all the meters used were calibrated using 30% LEL CH_4 in air. As can be seen from Fig. 12, in general all catalytic combustion sensors calibrated to read % LEL CH_4 exhibited fairly accurate readings for % LEL CH_4, but relatively low % LEL pentane readouts (not unexpectedly, because of lower vapor pressure for pentane than methane). For example, for the HMX271 NiCd, the meter response to 30% LEL CH_4 was 29 ± 0.6% LEL, while that for the 30% LEL pentane was only 14 ± 0.0% LEL. The same trend was also observed for the MOS sensor response (at least for the CGS-90) as can be seen in Table 10. Hence, regardless of what sensor type is used as combustible gas sensor in personal monitors, a meter calibrated with methane can only approximate the presence or absence of other combustible gases; and effective use of either sensor types would require knowing what flammable gas to expect (or suspect) in the contaminated air so that the sensor can be calibrated to respond to this specific analyte with better accuracy.

Table 10. Selectivity data for monitors with MOS sensor as combustible gas detector.[a]

Model	MOS Sensor Response (% LEL CH4)			
	30% LEL CH4 (21% O2)	31% LEL CH4 (19.5% O2))	31% LEL CH4 (0% O2)	30% LEL Pentane (21% O2)
CGS-80 [b]	8 bars past 10%	8 bars past 10%	≥ 3 bars past 20%	None Detected
CGS-90 [b]	9 bars past 10%	9 bars past 10%	≥ 3 bars past 20%	2 bars

[a] Unlike in other parts of the study, the CGS-80 and CGS-90 MOS sensors were span calibrated using 30% LEL CH4 with the bar graph display set at 20% LEL CH4 (see Fig. 8).

[b] Note that the display for both MOS sensor readings for the CGS-80 and CGS-90 are nonlinear bar graphs as illustrated in Fig. 8. An entry of "None Detected" means that the target gas concentration in the sample was less than the minimum limit of the display (< 10% LEL), while an entry of "≥ 3 bars past 20% LEL" implies that the reading determined was beyond the maximum limit of the display (>20% LEL).
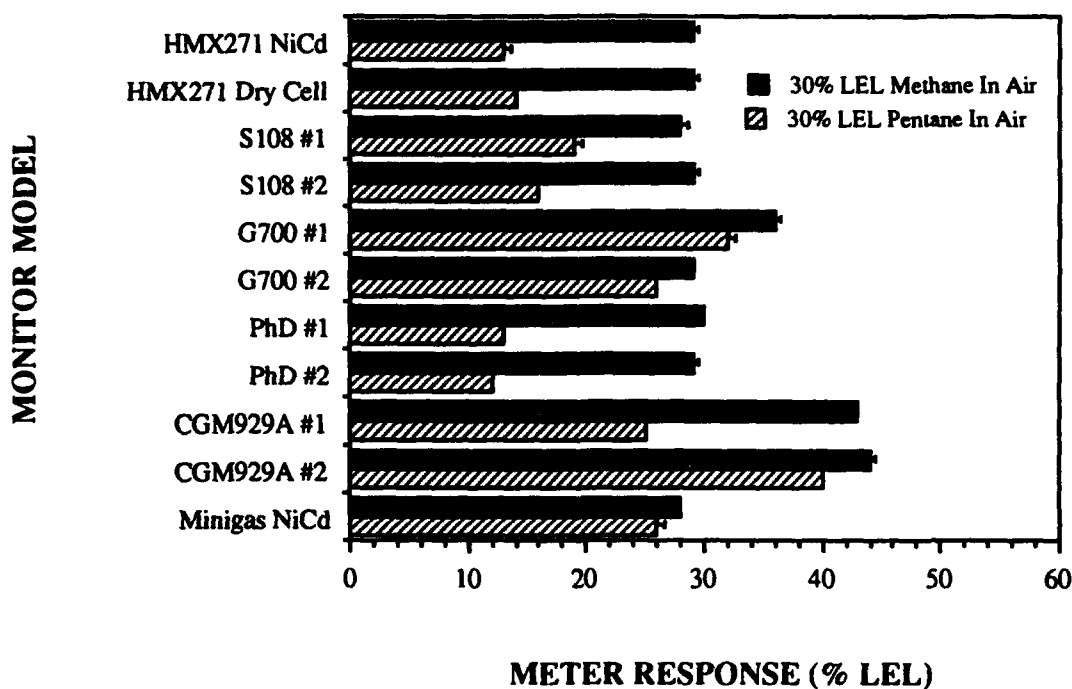
FIGURE 12   Difference of the catalytic combustion sensor response as illustrated for air mixtures containing 30% LEL methane and 30% LEL pentane.

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3. Alarm Response Time

Determination of the alarm response time to oxygen deficiency or overabundance, the presence of dangerous levels of combustible gas and toxic gas is an important (if not the most important) parameter to consider when deciding which is the best monitor to use. This is so because potential atmospheric hazards in confined spaces cannot be seen, although some of them (e.g., H_2S) can be unreliably detected by their distinct odors. More importantly, rapid alarm response is essential for recognizing the hazard with enough forewarning to take appropriate actions. This is especially critical when the danger develops while working inside the confined space (e.g., gas leaks from other sources). Hence, preferable are monitors which will most rapidly alert the user of unseen and unforeseen dangers from these atmospheric hazards. Finally, another significant reason why evaluation of alarm response time is very important is because although there are at least sixteen manufacturers of these combination gas monitors (see survey in Table 2 of Appendix B), not all these manufacturers are sensor makers. According to Vern Brown, president of Enmet Corporation (Ann Arbor, MI), only 10% of these instrument makers are sensor makers.[2] And since the technology for the sensors utilized have not advanced much lately, very little variation in terms of sensor performance (e.g., accuracy, selectivity and specificity, response time, etc.) are expected among these different models. At the most, sensor manufacturers are simply making the sensors smaller (for portability). State-of-the-art monitors, however, do differ a lot in terms of their ability to compute and the manner of sensor installation. Hence, the ability of the device to detect quickly (immediate dangers) and to alert the user will be due mainly to advances in the electronic circuitry, microprocessor, firmware and assembly design.

Experimentally, the alarm points were set at 19.5 for low O_2, 23.0% O_2 for high O_2, 10% LEL for CH_4, and 10 ppm for H_2S, unless stated otherwise. Finally, the target gas concentrations maintained inside the glove bag (see Fig. 4 for the set-up used) to determine alarm response time were: 24.7% O_2 for the high O_2 alarm, 24% LEL CH_4, and 30 ppm H_2S. For oxygen deficiency, the maximum O_2 concentration was never allowed to exceed 16.5% O_2. These concentrations were monitored using both PhD meters, except for the H_2S experiments in which either the HMX271 or S108 monitors were employed.

a. Oxygen Deficiency or Overabundance

A comparison of the alarm response times to oxygen deficiency or overabundance obtained for the various gas monitors evaluated can be seen in Figs. 13-16 with the error

bars corresponding to standard deviation. Monitor #1 corresponds to the version with the lower serial number, while monitor #2 corresponds to that with the higher serial number (as listed in Table 1). These data were obtained using the set-up shown in Fig. 4. Low and high oxygen alarm times were determined using 16 and 25% O_2 in N_2 mixtures with the alarm points set at 19.5 and 23.0% O_2, respectively.

LOW OXYGEN ALARM. Figure 13 illustrates the low (or deficient) oxygen alarm times measured for all meters. Repeatability of alarm times was good as can be seen from the figure. Note that some of the units which exhibited substantial variability in absolute times for low O_2 response (HMX271-Dry Cell and PhD #1 monitors) also exhibited, by a substantial margin, the fastest low O_2 response times. Alarm time reproducibility for the majority of the same model pairs was also acceptable (see plots for HMX271, S108, G700, PhD and MiniGas), allowing for trends to be judged. For example, the low oxygen alarm response times for the two G700 monitors were 23.33 ± 1.05 and 23.44 ± 0.98 seconds. More importantly, results for the HMX271 and MiniGas monitor pairs clearly illustrate that the type of power source utilized does not affect alarm response time. The measured response times for the HMX271 were 1.39 ± 0.14 and 1.29 ± 0.52 seconds, and for the MiniGas 5.72 ± 0.30 and 7.61 ± 0.64 seconds for the NiCd and Dry Cell versions, respectively.

Analysis of the low oxygen alarm response times obtained for all the monitors evaluated reveals that the values measured range from 1.29 ± 0.52 seconds for the HMX271 (Dry Cell) to almost 24 seconds (i.e., 23.44 ± 0.98 seconds) for the G700 #2 monitor. More specifically, the low oxygen alarm times obtained can be ranked as follows:

HMX271 *[1.34]* < PhD *[3.19]* < MiniGas *[6.66]* < S108 *[11.51]* ≈ CGM929A *[11.54]* < CGS-90 *[14.19]* < CGS-80 *[16.46]* < Compur Tritox M *[17.54]* and D *[19.33]* < G700 *[23.38]*

with the average response times in seconds for the various models indicated in square brackets. Note that the average values reported (in square brackets) for each model correspond to the pooled data for each model pair, except for the CGS-80, CGS-90, Compur Tritox D and Compur Tritox M wherein only one of each was supplied. Overall, only three monitor models (i.e., HMX271, PhD and MiniGas) had alarm times less than 10 seconds consistently, with the HMX271 and PhD meters having alarm times less than 5 seconds, although the CGM929A #1 had a low O_2 alarm time of only 8.70 seconds. Hence, based on these results alone, one can conclude that the HMX271, PhD and

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MiniGas meters are the best combination as monitors to use as safety device for O_2 concentration.

ALARM RESPONSE TIME TO OXYGEN DEFICIENCY (s)
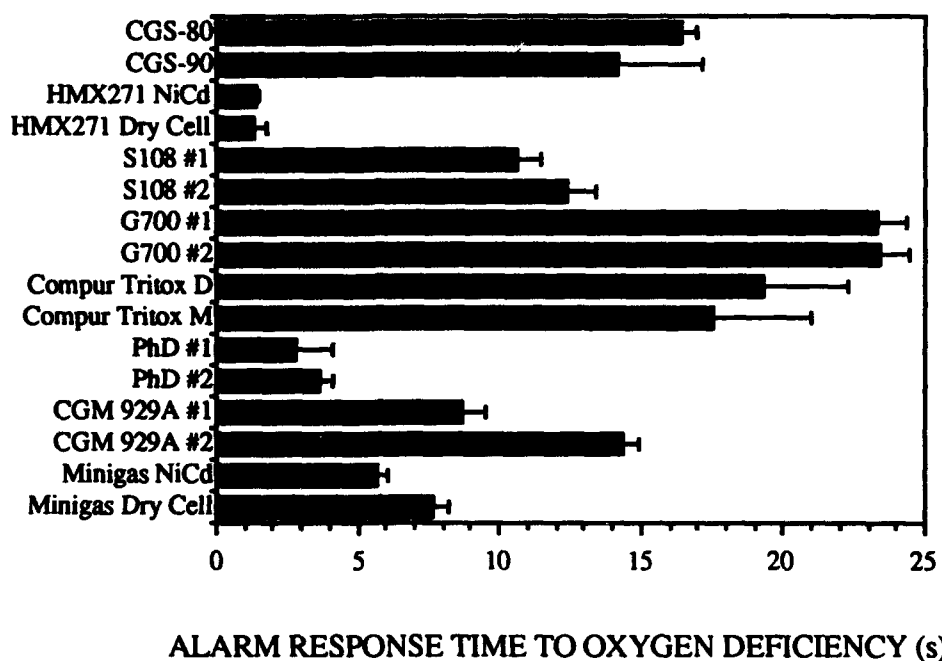
FIGURE 13   Alarm response time to oxygen deficiency as determined using a 16% oxygen in nitrogen test mixture with the alarm point set at 19.5% O_2.
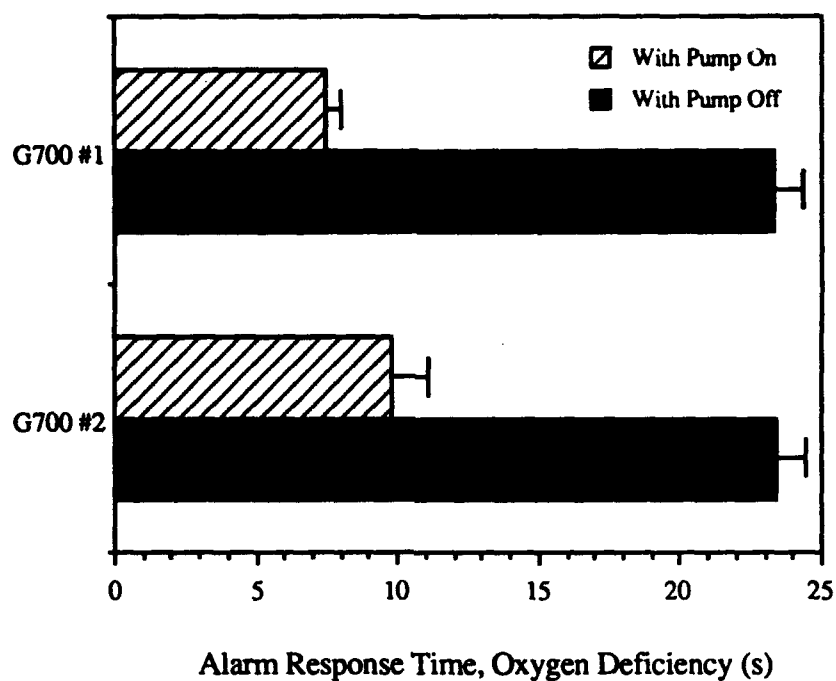
FIGURE 14. Effect of the sampling pump on the alarm response time for oxygen deficiency, determined using a 16% oxygen test gas with the alarm point set at 19.5% oxygen for the model G700 monitor.
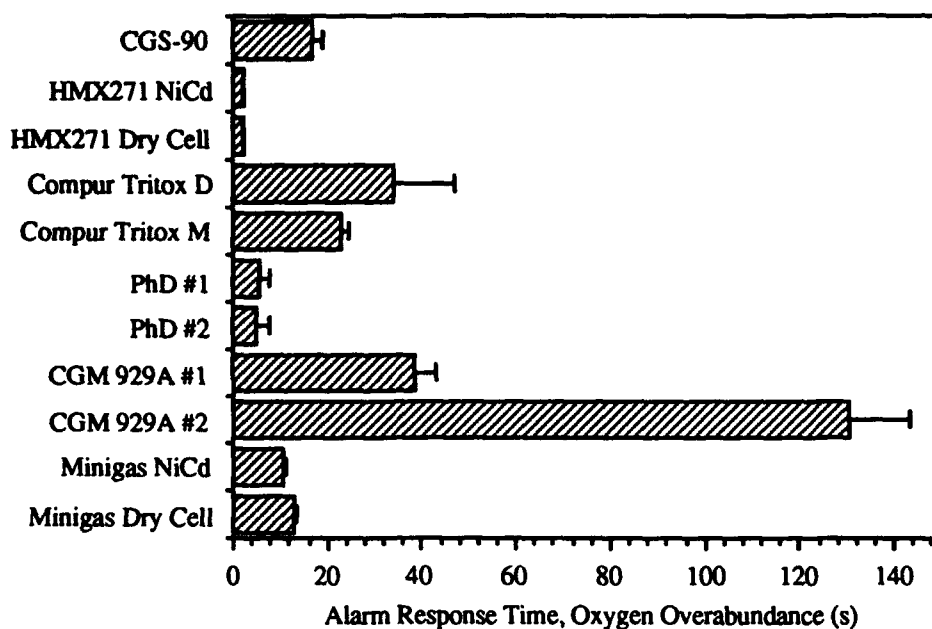
FIGURE 15   Alarm response time to oxygen overabundance, determined using 25% oxygen in nitrogen test mixture with the alarm point set at 23% O_2.
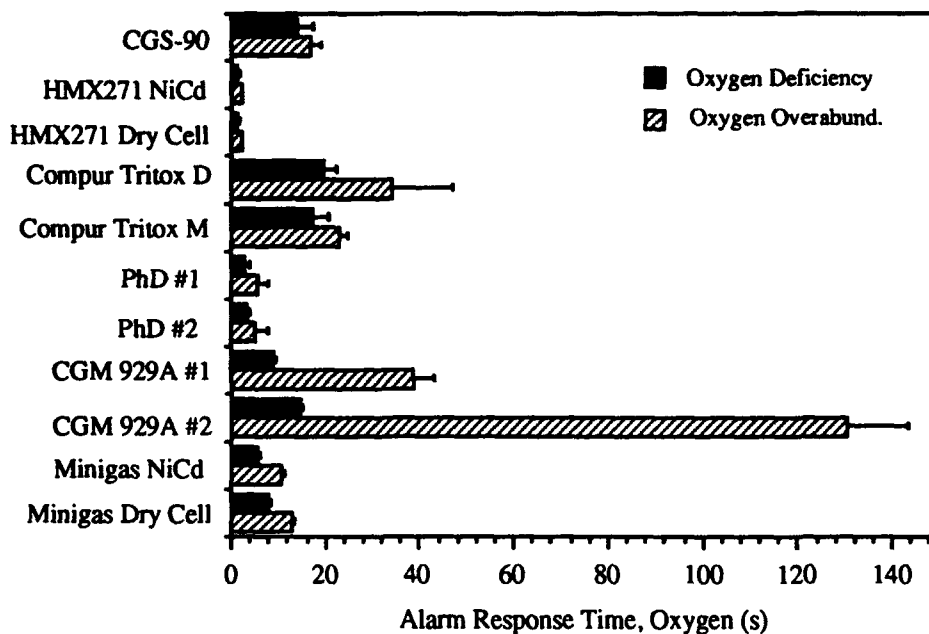
FIGURE 16   Alarm response time to oxygen deficiency and overabundance for the different monitors.

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Another trend illustrated in Fig. 13 is the reduction in alarm response time due to the sampling mode utilized. All the monitors evaluated operate in the diffusion mode for gas sampling (i.e., the analyte reaches the gas sensors by diffusion) except the Compur Tritox M and G700 which are both equipped with built-in, motorized sampling pumps. The major difference between these latter models is that the Compur Tritox M always runs in the pump mode while the G700 allows the operator to select between the two sampling modes (i.e., either diffusion or pump modes). It is emphasized that the results shown in Fig. 13 for the G700 meters are for the monitor operated in the diffusion mode. The data (Figure 13) for the Compur Tritox D and Compur Tritox M , however, clearly do not show a significant reduction in alarm response times for the motorized pump version. The alarm times for the D and M models obtained were 19.33 and 17.54 seconds, respectively, which represents only a 1.79 second (or almost 10%) decrease in the low oxygen alarm response time. The reduction was not that significant because of the low suction rate of the Compur Tritox M pump. Specifically, the measured volumetric flow rate for the Compur Tritox M model was only 3.0 mL/s, while similar values for the G700 #1 and #2 were equal to 14.9 and 14.3 mL/s, respectively. Hence, the pump rate for the two G700 meters is almost five times greater than that for the Compur Tritox M. A more drastic reduction in alarm response time was, however, observed for the G700 gas meters (see Fig. 14) wherein the average response times for the model pair decreased from 23.38 ± 0.91 seconds with the pump off to 8.65 ± 1.54 seconds with the pump on, which corresponds to a 14.73 second (or 63%) reduction in alarm response time. The very fast alarm response times for the HMX271, PhD and MiniGas monitors become even more impressive when their alarm times (which were obtained using only the diffusion sampling mode) are compared to similar values for the Compur Tritox M and G700 gas meters operated in the pump mode.

HIGH OXYGEN ALARM. Figure 15 shows the high (or overabundant) oxygen alarm times measured for all the monitors equipped with high O_2 alarms. No data were obtained for the CGS-80 and G700 meters because these devices are not equipped with a high oxygen alarm. Similarly, no high oxygen alarm values are reported for the two S108 monitors in Fig. 15 because the high oxygen alarm for this model was factory set at 25.0%, which cannot be altered.

Similar to the results obtained for the low oxygen alarm points, the reproducibility of the high oxygen alarm points for each monitor and for the same model pairs are acceptable. An exception to this, however, was observed for the two CGM929A monitors wherein the CGM929A #1 meter had a high oxygen alarm time of 38.63 ± 4.50 seconds while the CGM929A #2 counterpart had an alarm time equal to 130.31 ± 12.76 seconds. It is not

known why such a discrepancy was observed for the two CGM929A meters, but these results parallel those obtained for the same monitors under the low O_2 conditions. As can be seen from Fig. 13, the mean low O_2 alarm time for CGM929A #1 was 8.70 ± 0.85 seconds while a similar parameter for the CGM929A #2 meter was equal to 14.38 ± 0.57 seconds.

All eleven instruments for which we determined alarm response times for oxygen overabundance exhibited similar response patterns as for oxygen deficiency, though the Compur Tritox D and the two PhD gas monitors were intermediate in reproducibility for replicate measurements using the same monitor. The results obtained for the HMX271 and MiniGas monitors are further evidence that the type of power-source used does not significantly affect alarm response time. Specifically, the high oxygen alarm response times for the HMX271 were 2.11 ± 0.24 and 2.01 ± 0.16 seconds and those for the MiniGas were 10.45 ± 0.71 and 13.00 ± 0.55 seconds for the NiCd and Dry Cell versions, respectively.

Overall, the values obtained for the high oxygen alarm time range from 2.01 ± 0.16 seconds for the HMX271 (Dry Cell) to greater than 120 seconds (or two minutes) for the CGM929A #2 monitor. More specifically, the high oxygen alarm times measured can be ranked as follows:

HMX271 [2.06] < PhD [5.22] < MiniGas [11.73] < CGS-90 [16.89] < Compur Tritox M [23.01] < Compur Tritox D [34.13] < CGM929A [84.47]

with the average response times in seconds for the various models indicated in square brackets. Again, similar to the results obtained for the low O_2 experiments, the HMX271, PhD and MiniGas models exhibited the fastest alarm times to oxygen abundance. It should also be noted that among the seven models studied, only the HMX271, PhD and MiniGas had alarm times less than 20 seconds with only the HMX271 and PhD monitors having high oxygen alarm times less than 10 seconds. This time, however, the advantage of using a sampling pump for reducing alarm response time is clearly demonstrated by the Compur Tritox monitors. The alarm times for the Compur Tritox D and M models obtained were 34.13 and 23.01 seconds, respectively, which represents an 11.12 second (or a 33%) decrease in the high oxygen alarm response time.

Finally, Fig. 16 shows a combination plot of the alarm response times to oxygen deficiency and overabundance for the different monitors. The most obvious trend that can

be seen from the latter figure is that in all cases the high oxygen alarm time is greater than the low oxygen alarm time. This is most likely just a manifestation of the fact that prior to exposure to "bad" atmosphere, the oxygen sensors were exposed to "clean" or fresh air containing approximately 20.9% oxygen, which is closer to the low oxygen alarm point (i.e., 19.5 versus 23.0% oxygen for the high O_2 alarm point). Additionally, 16.1 and 25.4% oxygen standards were used to determine the low and high oxygen alarm times, respectively, which corresponds to approximately a 3.5 versus a 2.5% difference from the low and high oxygen alarm settings, respectively. The more important trend shown in Fig. 16, however, is that <u>regardless of which oxygen alarm point is considered, the HMX271, PhD and MiniGas monitors gave the fastest oxygen alarm response</u>, in ascending order. Note that for the HMX271, the measured low and high oxygen response times were 1.39 and 2.11 seconds for the NiCd, and 1.29 and 2.01 seconds for the Dry Cell versions, respectively.

b. Combustible Gas

Comparison of the alarm times to the presence of unacceptable concentrations of combustible gas (CH_4) is presented in Figure 17. Response time to CH_4 was determined using 30% LEL CH_4 in air with the alarm point set at 10% LEL. Note two exceptions, however. The combustible gas alarm point for the CGS-90 was set at 16% LEL CH_4 (the same concentration as that for the span calibration gas used for this monitor), while the alarm point for the MiniGas was factory pre-set at 20% LEL and could not be changed. By definition, the LEL value for any combustible gas refers to the lowest concentration in air at which the gas can ignite. Hence, alarm points generally are set well below the gas LEL (usually less than 50% LEL) for a margin of safety.

As illustrated in Figure 17 and similar to the results for the oxygen sensor responses, reproducibility of the combustible gas sensor alarm response times was very good. This was true both of the repeatability of measurements for a given monitor and of the comparison between duplicate monitors. The alarm times obtained for combustible gas ranged from 2.48 ± 0.59 seconds (CGS-80) to 20.53 ± 14.56 seconds (Compur Tritox D). Overall, the combustible gas sensor alarm response times determined can be ranked as follows:

CGS-80 [2.48] ≈ HMX271 [2.55] < CGS-90 [4.43 with alarm set at 16% LEL] < PhD [6.97] ≤ S108 [7.94] ≈ CGM929A [8.17] < MiniGas [12.82 with alarm set at 20% LEL] ≤ Compur Tritox M [13.98] < G700 [16.35] < Compur Tritox D [20.53]

with the average response times in seconds for the different models or monitor pairs listed in square brackets. Unlike the results obtained for the low and high O_2 alarm response, more than half of the meters studied exhibited alarm times less than 10 seconds (i.e., for the CGS-80, HMX271, CGS-90, PhD, S108 and CGM929A), with the first three meters in the list exhibiting alarm times of < 5 seconds).

ALARM RESPONSE TIME TO 30% LEL METHANE (s)

FIGURE 17. Comparison of the alarm response time to the presence of combustible gas as determined using a 30% LEL methane in air mixture with the alarm point set at 10% LEL. Note, however, that the combustible alarm point for the CGS-90 was set at 16% LEL CH_4 (the same concentration as that for the span calibration gas used for the CGS-90), while the alarm point for the MiniGas was factory set at 20% LEL (which cannot be altered).

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Another important trend that can be observed from Fig. 17 is the effect of the combustible gas sensor type on the alarm time. As indicated by Arenas, *et al.*,[1] the two most popular sensor types used as combustible gas detector in portable gas monitors for confined space applications are the catalytic combustion and MOS sensors. Of the monitors studied, the CGS-80 and CGS-90 models use MOS sensors for flammable gas detection. Hence, based on the results obtained for the CGS-80 and HMX271 meters (which both exhibited alarm times of approximately 2.5 seconds), it appears that both MOS and catalytic combustion sensors provide equivalent and rapid alarm response to combustible or flammable atmospheres. Finally, a comparison of the results obtained for the two Compur Tritox models reaffirms the effectiveness of using a sampling pump to lowering the alarm response time. For the latter monitors, a 6.55 second or 31.9% decrease in alarm response time was obtained via the use of the pump. Similar results were also observed for both G700 meters (see Fig. 20); the average decrease in alarm response time observed when the motorized sampling pump was used equaled 7.02 seconds or 42.9%.

c. Toxic Gas Sensor

Figure 19 shows a comparison of the alarm response times to the presence of H_2S obtained using 35 ppm H_2S in air as test gas with the alarm points set at the TLV-TWA (8 hr.) of 10 ppm H_2S. No data are reported for the MiniGas monitors since these were supplied with an instantaneous H_2S alarm point factory-set at 50 ppm. Alarm times for the PhD meters, on the other hand, were determined approximately two weeks later than the rest of the data reported in Fig. 19 because the PhD meters needed servicing when the other alarm times were measured. Finally, it should be noted that the average alarm time reported for the CGS-90 meter was determined visually (i.e., by noting when the nonlinear bar graph display gets to 10 ppm H_2S) because the instrument automatically sets the alarm point at the same toxic gas concentration as that of the span calibration gas used which was an 18 ppm H_2S in air mixture.
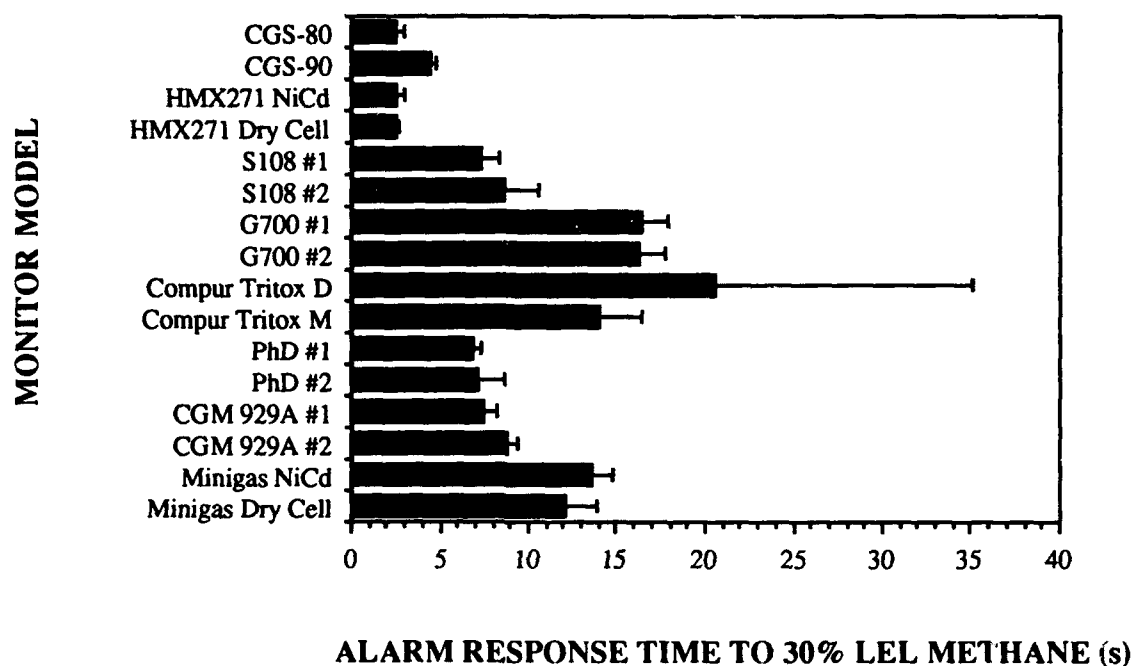
ALARM RESPONSE TIME TO 30% LEL METHANE (s)
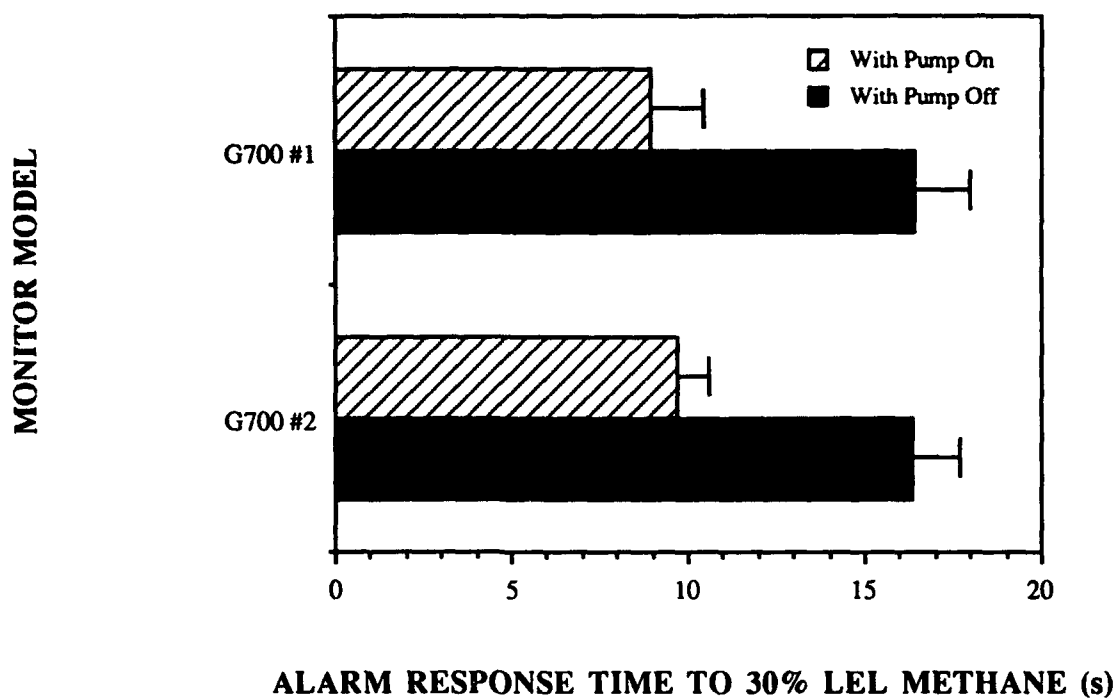
FIGURE 18.   Effect of the sampling pump on the alarm response time to the presence of
combustible gas as determined using 30% LEL methane with the alarm
point set at 10% LEL for the model G700 monitor.

ALARM RESPONSE TIME TO 35 ppm H_2 S (s)
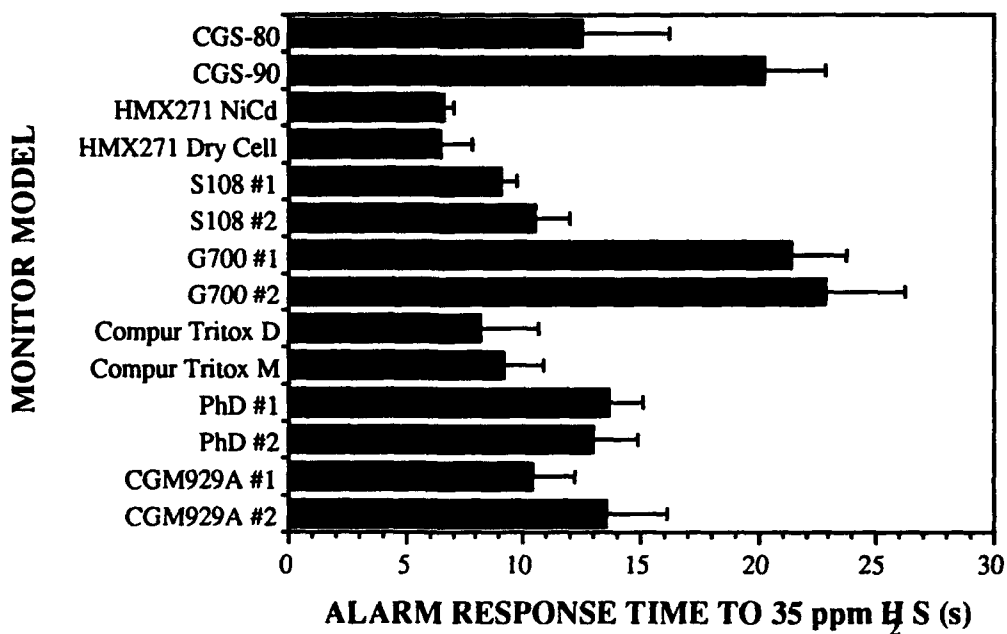
FIGURE 19.   Comparison of alarm response time to toxic levels of hydrogen sulfide.

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Similar to the results obtained for the oxygen and combustible gas sensors, reproducibility of the toxic gas alarm response for each model was very good in absolute terms (i.e., replicate measurements for a single instrument were within 5 seconds of each other in all cases), though this reproducibility was not as good for H_2S as for the other gases. The difference in average alarm response times between instruments comprising a model pair ranged from 0.16 seconds for the HMX271 to 3.21 seconds for the CGM929A.

Overall, the toxic gas alarm response times measured range from 6.47 ± 1.32 seconds for the HMX271 (Dry Cell) to 22.83 ± 3.40 seconds for the G700 #2. More specifically, the H_2S alarm times can be ranked as follows:

HMX271 *[6.55]* < Compur Tritox D *[8.14]* ≈ Compur Tritox M *[9.18]* ≈ S108 *[9.80]* < CGM929A *[11.96]* ≈ CGS-80 *[12.48]* ≈ PhD *[13.36]* < CGS-90 *[20.26]* < G700 *[22.10]*

The average response times in seconds for the different models is listed in square brackets. Consistent with the results obtained for O_2 and combustible gas alarms, the HMX271 again exhibited the fastest response to the toxic gas. Finally, four of the ten models evaluated (i.e., the HMX271, Compur Tritox D and M, and S108) exhibited average alarm response times to 35 ppm H_2S of less than 10 seconds.

Regarding the effect of the type of toxic gas sensor used, it can be seen from the previous ranking that three of six models using electrochemical cells exhibited faster alarm response times for H_2S than those with MOS sensors (CGS-80 and CGS-90). Exceptions were the G700, which was clearly slower, and the PhD and CGM units which were not significantly different. It is emphasized that no direct evidence was obtained to indicate that differences were actually due to the sensor type employed and not to the electronics or diffusion capability of each particular monitor.

Finally, comparison of the results for the Compur Tritox D and M versions reveals no advantage in terms of alarm response time to H_2S. The H_2S alarm time obtained for the Compur Tritox D was 8.14 ± 2.50 seconds, while the corresponding value for the Compur Tritox M (which operates in the pump mode) was 9.18 ± 1.67 seconds. Hence, an even slightly larger average response time was observed for the meter which samples the atmospheric gas in the pump mode. Results for the G700 (see Fig. 20 which compares the alarm response times for the G700 operated in the pump and diffusion modes), however,

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reveal an average lowering of the response time from 22.10 to 7.75 seconds in the diffusion and pump modes, respectively, or a 14.35 second (or 65%) decrease in H_2S alarm response time. Note that as has been indicated previously, the pump sampling rate for the G700 is almost five times that for the Compur Tritox M.

4. Remote Sampling Capability

For use in confined space monitoring, in which the first task required before entering the enclosed area involves analyzing the confined atmosphere for possible contamination, remote sampling capability is as important as alarm time. As stated earlier in the results and discussion section of this report, one way of obtaining remote target gas concentrations in the enclosed space is by using a sampling pump to draw air samples from the confined space to the sensor compartment of the portable monitor. Hence, before the air sample can be detected, they must first travel the length of the sampling tube employed.
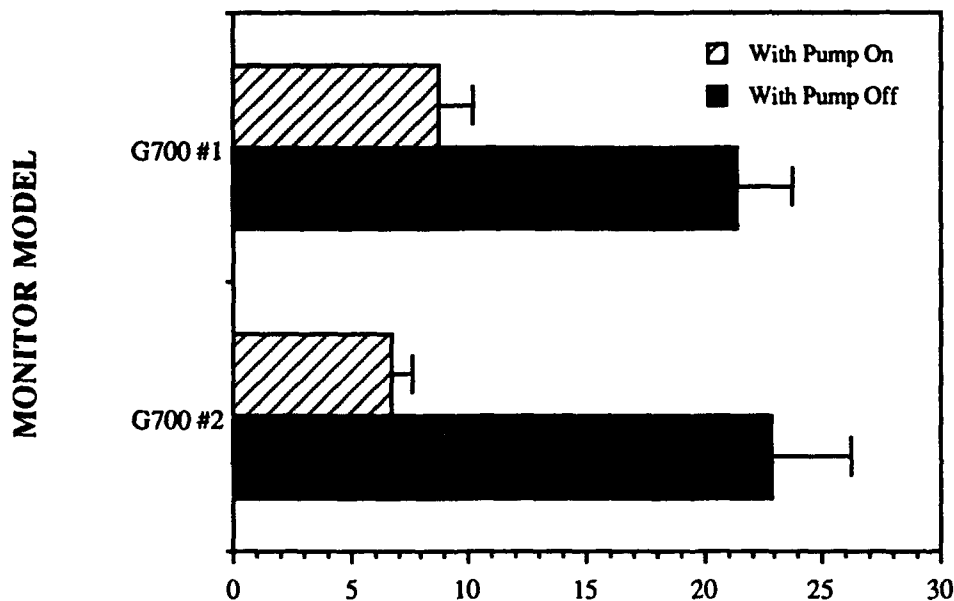
ALARM RESPONSE TIME TO 35 ppm HYDROGEN SULFIDE (s)

FIGURE 20.   Effect of the sampling pump on the alarm response time to the presence of toxic gas as determined using 35 ppm hydrogen sulfide with the alarm point set at 10 ppm for the model G700 monitor.

Only two models investigated were equipped with internal, motorized sampling pumps, namely the Compur Tritox M and G700, with volumetric pump rates of approximately 3.0 and 14.6 mL/s, respectively. The latter pump rates were determined using a 100 mL Soap Film Flowmeter (HP part number 0101-0113, Hewlett-Packard Company, San Fernando, CA) with graduation marks at 1, 10 and 100 mL. To determine

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the pump flow rate, the time required for the soap film to travel 90 mL was measured. The remote sensing characteristics of the other monitors (i.e., HMX271, PhD, CGM929A and MiniGas) were determined using a manual pump which consisted of a rubber bulb aspirator located along the tubing closer to the monitor (as shown in Fig. 5 for the PhD meter). The test gases used consisted of 16 and 25% O_2 in N_2, 30% LEL CH_4 and 35 ppm H_2S in air.

a. Steady-State Readout

Tables 11 and 12 show the target gas steady-state concentration and the approximate time required to reach that reading by remote sampling in the pump mode. Comparison of the meter readouts in Table 11 with the results for diffusion mode remote sampling (see Table 3 for the O_2 data, Table 5 for the CH_4 data, and Table 7 for the H_2S data) reveals that approximately equal gas concentrations can be obtained using either the pump or diffusion mode for remote sampling.

Table 11. Steady-state concentration of target gas determined in diffusion mode and in remote sampling in the pumped mode.

Model (SN) [a, b]	Meter Response at different gas concentrations							
	16.08% O_2		25.45% O_2		31.5% LEL CH_4		35.1 ppm H_2S	
	diff'n	pump	diff'n	pump	diff'n	pump	diff'n	pump
G700 (91090289)	15.8	15.8	24.5	24.8	31	31	27	44
G700 (91090290)	15.9	15.8	24.6	24.8	31	32	27	41
Compur Tritox M	15.9	15.9	24.5	24.6	35	18	72	90
Compur Tritox D	16.0	NA[c]	24.3	NA	36	NA	48	NA
HMX271 (NiCd)	15.9	16.3	24.5	23.9	30	24	28	41
HMX271 (Dry Cell)	16.3	19.1	25.1	26.2	29	40	28	34
PhD (DK108-1428)	15.3	15.2	25.1	25.2	31	33	25	26
PhD (DK108-1429)	15.3	15.8	25.1	24.9	30	32	25	26
CGS-80[d]	16.2	NA	24.7	NA	25[e]	NA	19	NA
CGS-90[d]	15.6	NA	24.8	NA	25[e]	NA	>23	NA
CGM929A (4571)	15.9	15.5	24.7	25.0	35	32	25	25
CGM929A (4572)	16.2	16.0	24.3	24.4	45	33	25	23
MiniGas (NiCd)	15.9	16.0	24.7	24.5	30	24	28	39
MiniGas (Dry Cell)	15.9	16.2	24.8	24.6	29	29	30	47
S108 (91361634)	15.9	NA	24.4	NA	24	NA	27	NA
S108 (91361656)	15.8	NA	24.3	NA	28	NA	27	NA
Median	.9		24.5		27		30	

[a] SN = Serial Number.

[b] Only the G700 and Compur Tritox M meters have motorized internal pumps.

[c] NA, option not available; m, data missing; X, unit did not function during test.

[d] Readout is a segmented bar graph.

[e] Monitor only reads to ≈23%LEL. This value was obtained by extrapolation of response at 20% LEL

Table 12. Time to reach steady-state reading for target gas concentration by remote sampling in the pump mode. [a]

Model (SN) [b, c]	Time to steady-state reading (sec) @			
	16.08% O_2	25.45% O_2	31.5% LEL CH_4	35.1 ppm H_2S
G700 (91090289)	20	20	20	40
G700 (91090290)	20	20	20	40
Compur Tritox M	30	60	30	60
HMX271 (NiCd)	60	60	30	40
HMX271 (Dry Cell)	60	30	30	35
PhD (DK108-1428)	45	30	15	40
PhD (DK108-1429)	45	30	15	40
CGM929A (4571)	90	60	60	30
CGM929A (4572)	150	30	60	40
MiniGas (NiCd)	40	30	60	45
MiniGas (Dry Cell)	40	30	30	45

[a] Steady-state concentration of target gas refers to the constant reading obtained, which in most cases was also the highest meter response.

[b] SN = Serial Number.

[c] Only the G700 and Compur Tritox M meters have motorized internal pumps. Others used a manual bulb type pump.

In general, the % O_2 readings in Table 11 using remote sampling in the pump mode agree very well with corresponding values in Table 3. For example, using the pump mode the steady-state concentration obtained using the 16.08% O_2 mixture for the G700 #1 was 15.8% O_2 (see Table 11). Similar values for the diffusion mode (see Table 3) of remote sampling for the same monitor obtained were 15.7, 15.9 and 15.9% O_2 (or an average reading of 15.8% O_2). Agreement of the results for the CH_4 mixture was not as good except for the G700, PhD and MiniGas. For example, for the MiniGas (Dry Cell) model, the steady-state % LEL obtained using the pump mode was 29% LEL, the same average value indicated in Table 5 for the diffusion mode. It should be noted, however, that for the other monitors, the steady-state CH_4 concentration obtained using the pump mode were all less than corresponding values in Table 5, except for the HMX271 (Dry Cell), which may imply that the use of a more powerful motorized pump may be necessary. Note that in all cases, the maximum sampling time used was 5 minutes. The need to use more powerful pumps is consistent from a comparison of the CH_4 results obtained for the G700 and Compur Tritox M, wherein it has been determined that the pumping rate of the G700 was almost 5 times more powerful than that for the Compur model. For the G700 SN 91090289, average CH_4 readings in the pump and diffusion modes observed were both 31% LEL CH_4 as can be seen in Tables 11 and 5, respectively. For the Compur Tritox M, however, similar values were equal to 18 and 35% LEL CH_4 for the pump and diffusion modes, respectively. Results for the 35.1 ppm H_2S mixture, on the other hand, show that in general the steady-state H_2S reading obtained using the pump mode were greater than corresponding values in Table 7 (obtained in the diffusion mode), except for the PhD and CGM929A meters which exhibited approximately equal readings in both sampling modes. For example, for the G700 #1 meter, average H_2S readings in the pump and diffusion modes were 44 and 27 ppm, respectively, as indicated in Tables 11 and 7. Finally, as can be seen in Table 12, the minimum time required to reach equilibrium conditions for remote sensing in the pump mode is approximately 15 seconds using 2 m tubes with internal diameters of 5 mm. The maximum time observed to reach steady-state conditions was 150 seconds (for the CGM929A #2 with 16.08% O_2 as test gas).

b. Alarm Response Time

A comparison of the alarm response times obtained for remote sampling using the pump versus the diffusion modes can be seen in Figs. 21-25. Similar to the previous discussion, the alarm data used for the diffusion mode are the same as those in Figs. 13,

15, 17 and 21. It is emphasized, however, that the diffusion data for the Compur Tritox M are actually also in the pump mode but without the 1.98 m tubing.

In general, using the monitors for sensing is expected to yield delayed alarm responses, and the delay will be longer for longer sample tubes. Hence, the limiting factor will be how fast the sample travels the length of the tubing. This is evident from the comparison of the results obtained for the HMX271 meters for the O_2 and CH_4 versus the H_2S systems. For the HMX271, it took < 3 seconds (in the diffusion mode) for the meters to alarm in O_2 deficient, or O_2 overabundant or flammable atmospheres. For example, the alarm response times (of the HMX271) to O_2 deficiency increased from 1.39 ± 0.14 seconds in the diffusion mode to 3.02 ± 0.43 seconds in the pump mode. The use of a powerful sampling pump can compensate for the relatively slow alarm response in the diffusion mode. This is illustrated by the results obtained for the two G700 and Compur Tritox M monitors. Note that as stated earlier, the pump rate for the G700 is approximately 5 times greater than that for the Compur Tritox M model. For the G700 meters, response time in the pump mode was always less than that in the diffusion mode. For example, the alarm response time of the G700 in the diffusion mode to 30% LEL CH_4, was the longest (see Fig. 26) among the monitors studied. Use of the sampling pump for remote sensing, however, lowered the response time from 16.40 ($\pm$ 1.58) to 10.00 ($\pm$ 1.59) seconds for the G700 #1, and from 16.31 ($\pm$ 1.41) to 9.48 ($\pm$ 1.16) seconds for the G700 #2. Hence, the relatively powerful sampling pump of the G700 compensated for its slow diffusion alarm response time to CH_4. The Compur Tritox M model, however, having the second slowest response among the models investigated (faster only than the G700), showed no benefit from using the sampling pump. Finally, Fig. 23 shows a comparison of the alarm response times to low and high O_2 using the remote sampling mode. as expected, the high O_2 alarm time is always greater than the low O_2 alarm time. An explanation for this trend has been provided elsewhere.
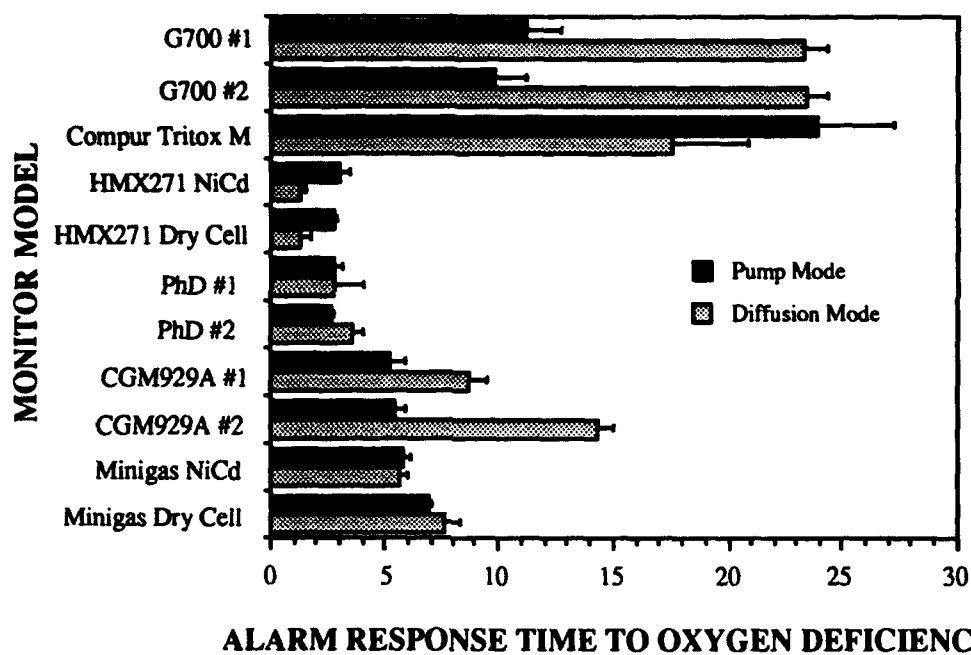
FIGURE 21. Comparison of the low O_2 alarm response times obtained using the pump sampling mode versus the diffusion sampling mode using a 16% O_2 mixture with the alarm point set at 19.5% O_2.
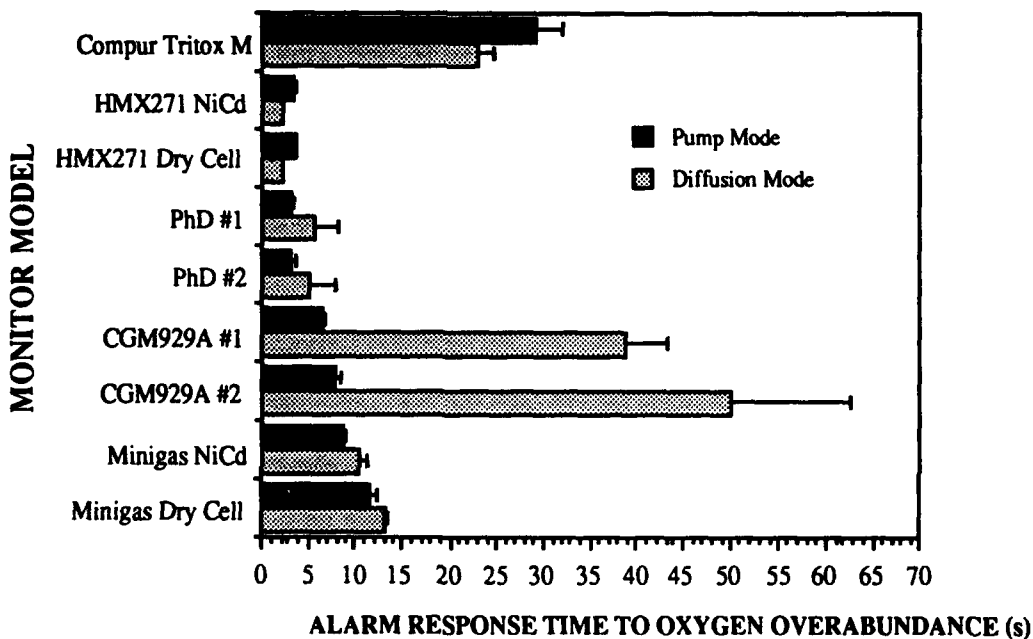
FIGURE 22. Comparison of the high O_2 alarm response times obtained using the pump sampling mode versus the diffusion sampling mode using a 25% O_2 mixture with the alarm point set at 23% O_2.
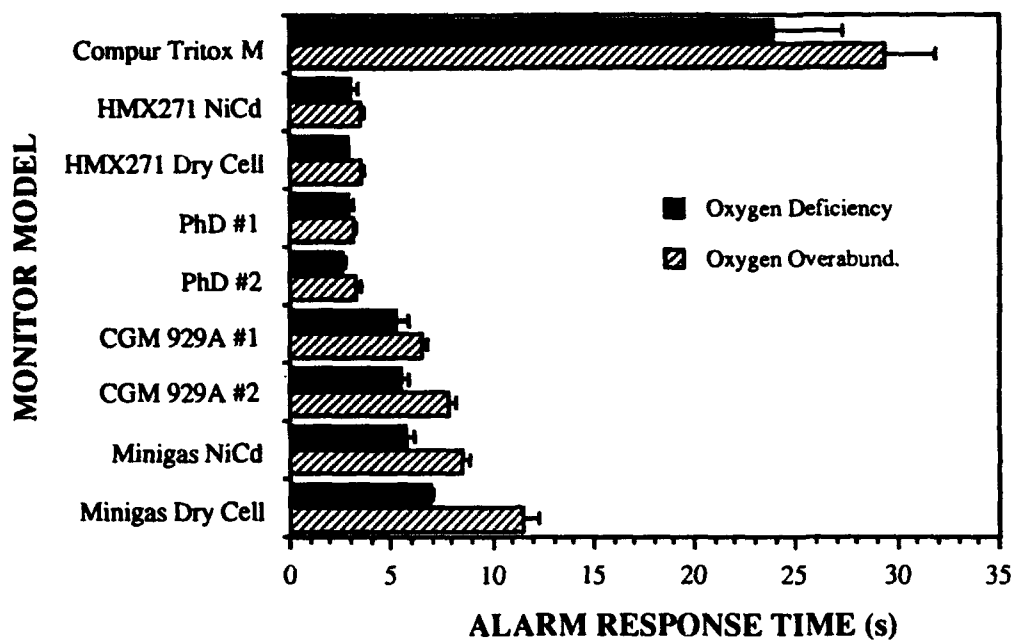
FIGURE 23. Combination plot for the alarm response time to oxygen deficiency and overabundance using the pump sampling mode.
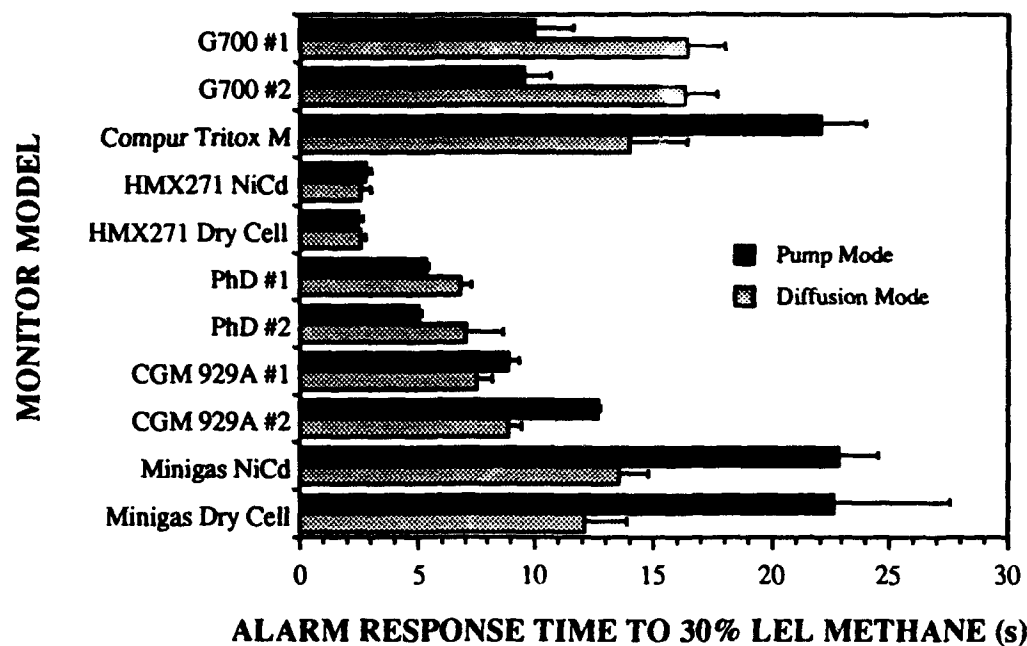
FIGURE 24.   Comparison of the combustible gas sensor alarm response times obtained
using the pump sampling mode versus the diffusion sampling mode using
a 30% LEL CH$_4$ in air mixture with the alarm point set at 10% LEL.
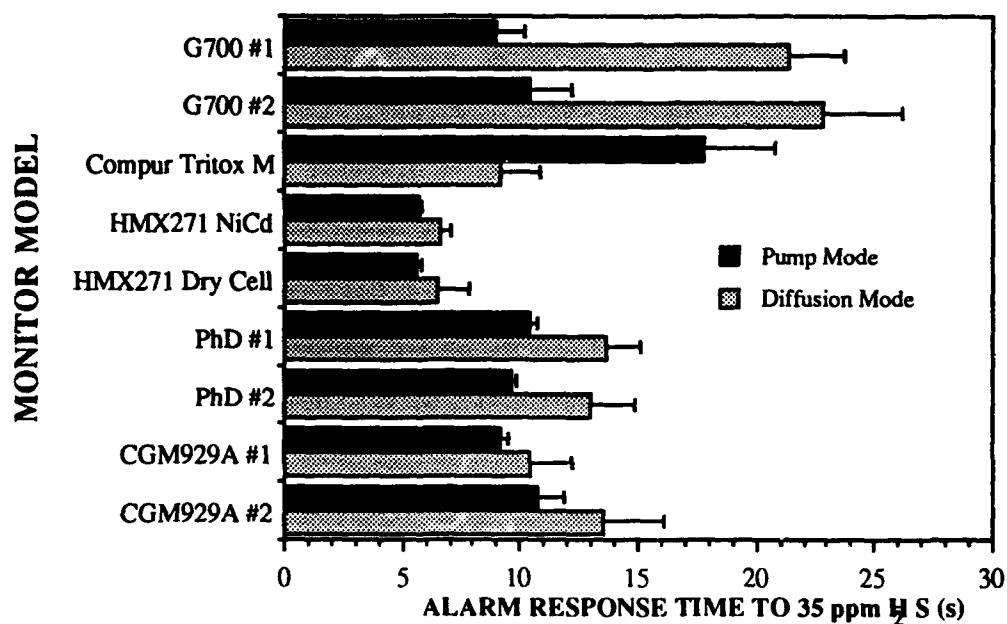
FIGURE 25.   Comparison of the toxic sensor alarm response times obtained using the
pump sampling mode versus the diffusion sampling mode using a 35 ppm
H$_2$S in air mixture with the alarm point set at 10 ppm.

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B. Evaluation of Operational Parameters and Other Physical Characteristics and Value Added Features

1. "Memory" For NiCd-Powered Monitors

The overall cell reaction for the nickel-cadmium (NiCd) battery may be summarized as follows:

$$2 \text{ NiO hydrate} + \text{Cd(OH)}_2 \underset{\substack{\text{NaOH} \\ \textit{Discharge}}}{\overset{\substack{\textit{Charge}}}{\rightleftharpoons}} 2 \text{ NiO (OH) hydrate} + \text{Cd}$$
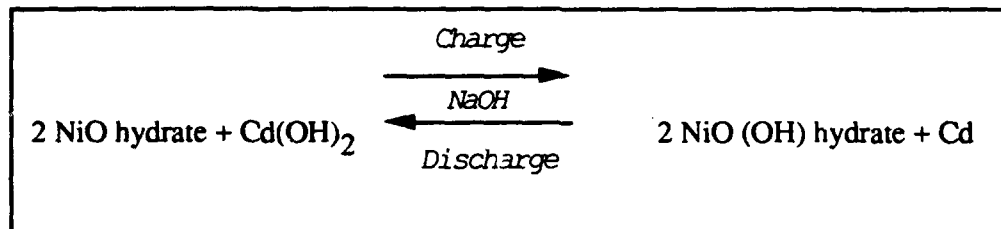
The battery is both mechanically rugged and dependable. During most of the discharge cycle (85 to 90%), the battery provides uniform voltage. Most NiCds can provide more than twenty years of useful life if the NiCd battery is not completely discharged (less than 80 to 85% discharge) during use. The applicable temperature range for both use and storage is from -29 to 60° C.[32]

The major disadvantage of using NiCd batteries as power source for portable instruments is the widely remarked "memory" phenomenon first observed by NASA engineers in the early 1960s.[23] As noted in a recent report by Gates Energy Products, "memory" for the NiCd battery refers to the phenomenon wherein "when the nickel-cadmium batteries were discharged, a fixed amount at a fixed rate, and then recharged, the cells would 'remember' the amount of discharge and give up only that amount even when called upon to deliver their full capacity".[23] According to Gates Energy Products,[23] "memory" in NiCd batteries does not exist and is a misconception. If this is the case, then it does not matter whether a rechargeable NiCd or dry cell is used as power supply for the portable gas monitors. More importantly, there would be no basis then, other than logistical considerations, as to why certain groups (e.g., the U.S. Coast Guard) should prefer dry cell-powered gas monitors over NiCd-powered ones.

The protocol used to investigate the existence of "memory" for NiCds involved periodic recharge-discharge cycling in which the monitor was used three hours per day followed by a 16 hour recharge. After ten cycles, the time required to fully discharge the battery, and the voltage of the battery during different stages of the discharge process were measured. The data obtained for the latter parameters are listed in Table 13 with a comparative plot of the manufacturer-specified expected minimum battery life and the

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observed analysis time after the cycling process shown in Fig. 26. The time to full discharge observed range from 7.2 hours for the CGS-90 to 17.2 hours for the MiniGas (NiCd). Hence, based solely on the latter values, a "memory" phenomenon was not seen, either with the rechargeable NiCds or with the lead-acid cells for the PhD and CGS-80 monitors. More importantly, except for the CGS-90, all of the fully charged batteries provided at least 10 hours of continuous operation time which, as can be seen from Fig. 26, exceeded the minimum expected battery life for these monitors. For example, after ten cycles of three hour use, the PhD #2 meter provided 13.4 hours of continuous analysis time which is consistent with the expected minimum battery life of 8 hours for a fully charged PhD unit based on manufacturer specification. A comparison of the results obtained for the Compur Tritox D and M which operates in the diffusion and pump sampling modes, respectively, suggest that the pump installed for the Compur Tritox M model is not a significant power burden. More specifically, the battery life obtained for the D and M versions were 10.4 and 9.8 hours (see Table 13), respectively. The expected battery delivery time for the latter two monitors are 10 and 8 hours, respectively. Finally, it is emphasized that shorter analysis time should be expected compared to the observed values listed in Table 13 depending on the number of alarm conditions encountered, and pumping time (i.e., if internal [e.g., for the G700] or external pumps are used which utilize the same power source as the monitor). The actual operation time in the latter cases should, however, still be at least 8 hours.

Table 13. Evaluation of "memory" for the NiCd-powered monitors.

Model (SN) [a,b,c]	Voltage After Final Charging	Voltage After 3 Hour Discharge	Voltage After Full Discharge [d]	Time To Full Discharge [d]
PhD(DK108-1428)[e]	6.5 V	6.2 V	5.5 V	11.9 hr
PhD(DK108-1429)[e]	6.5	6.2	5.5	13.4
CGS-80	8.7	7.9	7.3	12.0
CGS-90	10.8	9.7	7.7	7.2
G700 (91090289) [f]	100.%	60.%	23.%	10.3
HMX271 (NiCd)	5.4	5.1	4.7	11.9
Compur Tritox D	9.3	8.7	6.6	10.4
Compur Tritox M	9.3	8.7	6.7	9.8
Minigas (NiCd)	5.4	5.0	4.6	17.2
S108 (91361634)	8.1	7.6	7.0	10.3

[a] Only one G700 and one S108 monitors were used since IES was supplied with only one battery charger for each of the latter models.

[b] All the models listed were equipped with rechargeable NiCd batteries, except the PhD and CGS-80 monitors which were supplied with rechargeable lead-acid cells.

[c] SN = Serial Number.

[d] Full discharge does not mean 100% discharge, but very close to it.

[e] The battery voltages listed for the PhD were obtained from displayed values determined using the installed microprocessor.

[f] The NiCd battery of the G700 could not be accessed during the experiment, hence the voltage could not be monitored during the final discharge. Fortunately, the available battery capacity of the NiCd for the G700 can be displayed with the switch of a button. A reading of 80-100 corresponds to a fully charged battery, while values <20 means that the battery needs recharging.
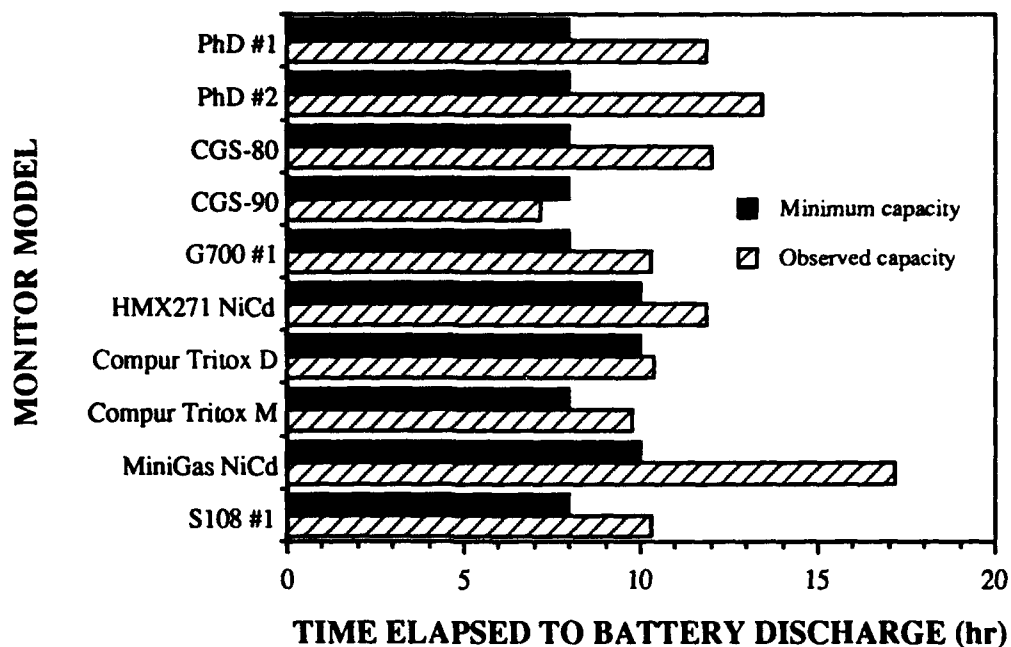
FIGURE 26. Comparison of the time elapsed to battery discharge after ten cycles of three hour discharges to the expected minimum battery capacity for the different portable gas monitors with rechargeable batteries. In the legend given, minimum capacity refers to the minimum number of hours expected during continuous operation for a fully charged battery.

2. Portability

According to LT Peter Kolasa, Eighth Coast Guard District Marine Safety Division Occupational Health Coordinator, monitor portability is usually the prime factor considered when deciding which is the best combination gas monitor to use. This is because the device is suppose to be carried or worn by the personnel at all times while inside the confined space or working area. Additionally, some confined spaces have limited area or room to move about (e.g., in manholes or sewers). Hence, it will be more convenient to carry a small and lighter monitor compared to a bulkier and heavier one, especially for prolonged periods of time during work. This is also why the current trend among state-of-the-art monitors is to decrease the overall size and weight of the instrument, which can only be achieved through the use of smaller gas sensors and improved electronic circuitry and software.

The portability of the different monitors was determined by measuring both the physical dimensions and the weights of the instruments. These values can be seen in Table 14, while a graphical comparison of the weights and sizes observed is shown in Figs. 27 and 28. Similar values based on information provided by the manufacturers can also be seen in Table 2. It should be noted that the dimensions listed in Table 14 include not only the main body of the monitor but all parts sticking out. Hence, this would include any protruding parts like switches, alarm lights, etc. Finally, the weights indicated in Table 14 are for the monitor plus all the sensors and battery pack supplied.

In terms of weight, the monitors can be ranked as follows in ascending order:

**HMX271 ≈ S108 < PhD ≈ MiniGas < G700 < CGM929A <
Compur Tritox D < Compur Tritox M < CGS-90 < CGS-80**

Overall, five models (HMX271, S108, PhD, MiniGas and G700) are under 1000 g, while one monitor (CGS-80) had a weight of almost 2500 g.

The lightest of these devices, the HMX271 Dry Cell, weighs only 520 g. Two other trends, readily seen in Table 14, are that use of NiCds rather than dry cells as power source adds weight to the unit as does the addition of an internal sampling pump.

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Table 14. Comparison of portability of the different multisensor gas monitors. [a]

Model (SN) [b]	Dimensions[d] L x W x H (cm)	Weight (g)[c]	Volume (cm³)	Girth L+W+H (cm)
PhD (DK108-1428)	18.60 x 10.85 x 5.95	824	1197	35.4
CGM929A (4571)	20.70 x 12.70 x 6.30	1188	1656	39.7
CGS-80	24.60 x 12.80 x 5.70	2407	1795	43.1
CGS-90	20.40 x 12.30 x 6.40	1540	1606	39.1
G700 (91090289)	22.70 x 8.90 x 5.90	925	1192	37.5
HMX271 (NiCd)	13.60 x 7.15 x 3.75	583	365	24.5
HMX271 (Dry Cell)	13.60 x 7.15 x 3.75	520	365	24.5
Compur Tritox D	24.10 x 11.00 x 4.70	1268	1246	39.8
Compur Tritox M	24.50 x 11.00 x 4.70	1362	1267	40.2
MiniGas (NiCd)	16.80 x 7.10 x 5.30	874	632	29.2
MiniGas (Dry Cell) [e]	15.50 x 7.25 x 5.50	832	618	28.3
S108 (91361634)	15.90 x 7.90 x 4.15	562	521	28.0

[a] The data listed are only for the "bare" monitor (i.e., without the carrying case, shoulder strap, etc.).

[b] SN = Serial Number.

[c] These values were determined using a Mettler PE 3600 Delta Range balance. Note that the weights listed include the power supply (i.e., rechargeable NiCd battery or lead-acid cell, or alkaline dry cells).

[d] Measurements given include those for the parts extending out of the main body of the monitor (e.g., switches, screws).

[e] Includes stainless steel belt clip.
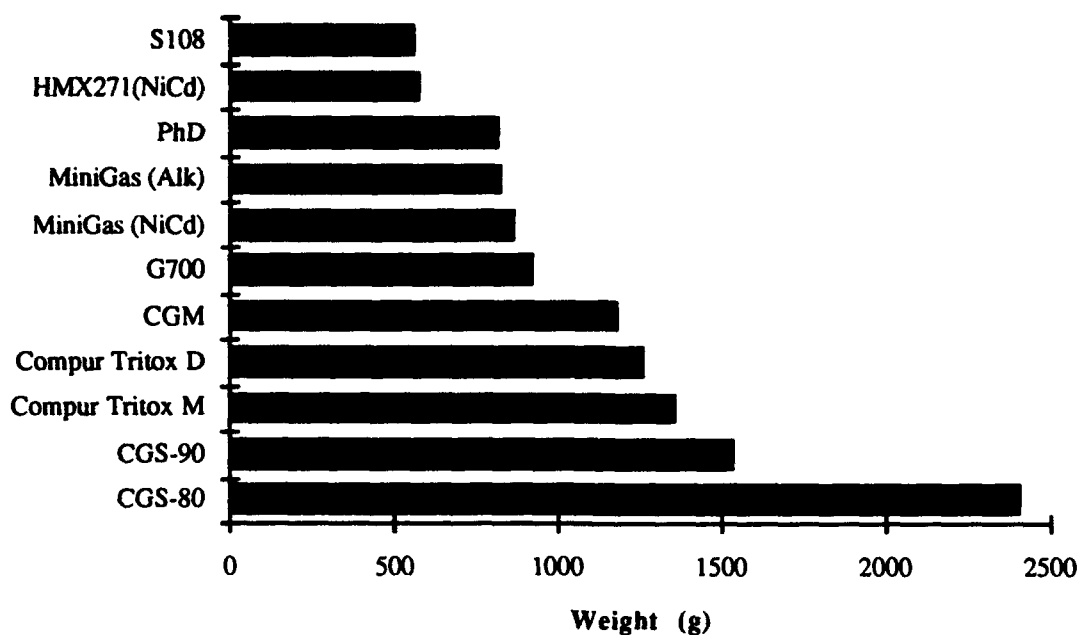
FIGURE 27. Comparison of the weights of the different portable gas monitors.
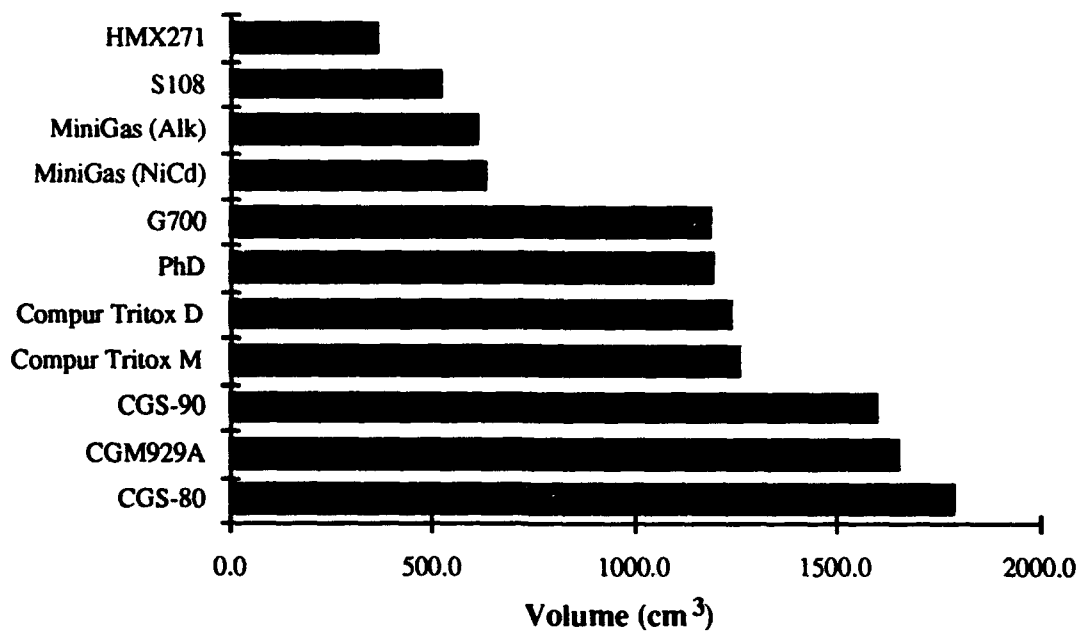
FIGURE 28. Comparison of the volume occupied by the different portable gas monitors.

The monitors can also be ranked in terms of length as follows, again in ascending order:

**HMX271 < S108 ≈ MiniGas < PhD < CGS-90 ≈ CGM929A < G700
< Compur Tritox D ≈ Compur Tritox M ≈ CGS-80**

Overall, values of the lengths measured range from 13.60 cm for the HMX271 to 24.60 cm for the CGS-80 (see Table 14 and Figs. 29-36). A comparison of the volumes occupied by the meters evaluated is listed in Table 14. Based on these data, the meters can be ranked as follows:

**HMX271 < S108 < MiniGas < G700 ≈ PhD ≈ Compur Tritox D or M
< CGS-90 ≈ CGM929A < CGS-80**

The meter volumes observed ranged from 400 ml (milliliter) for the HMX271 to 1800 ml for the CGS-80. Hence, the lightest and heaviest monitors were also the smallest and biggest in terms of size, respectively. Finally, only the HMX271 had a volume of less than 500 ml. The S108, however, does occupy a space of approximately 500ml.
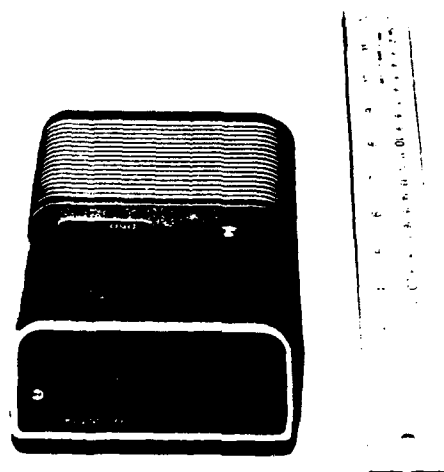
FIGURE 29.   PhD Atmospheric Monitor Model 1602 (Biosystems, Inc., Rockfall, CT).
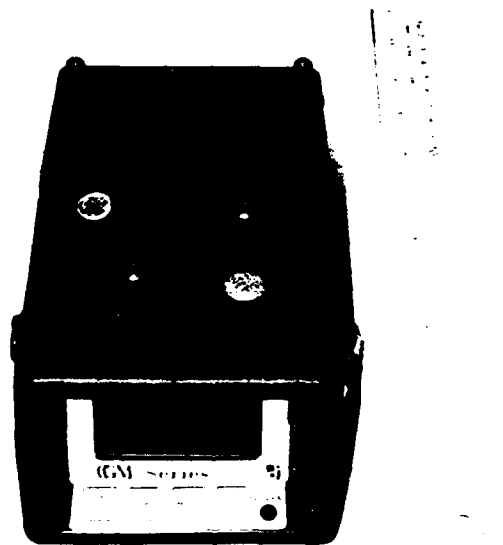
FIGURE 30.   Dynamation CGM Model 929A (Dynamation, Inc., Ann Arbor, MI).
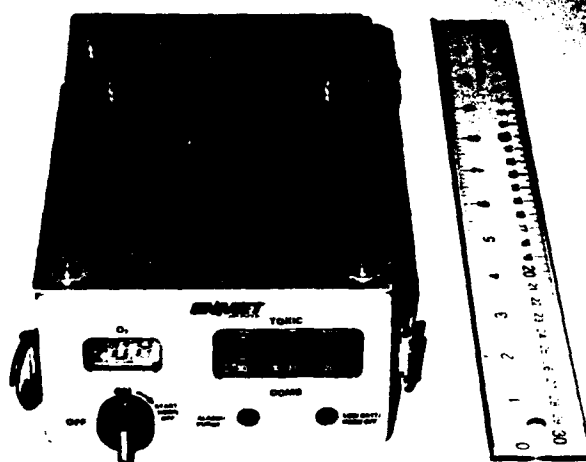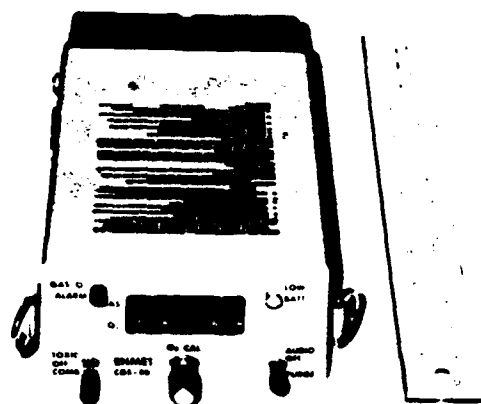
FIGURE 31. CGS-80 [Top] and CGS-90 [Bottom] (Enmet Corp., Ann Arbor, MI).

FIGURE 32.   Polytector G700 (GfG Gas Electronics, Inc., Clayton, MO).
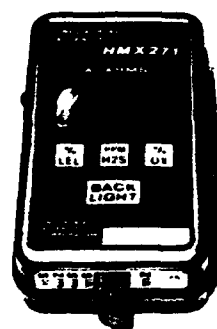
FIGURE 33. HMX271 (Industrial Scientific Corp., Oakdale, PA).
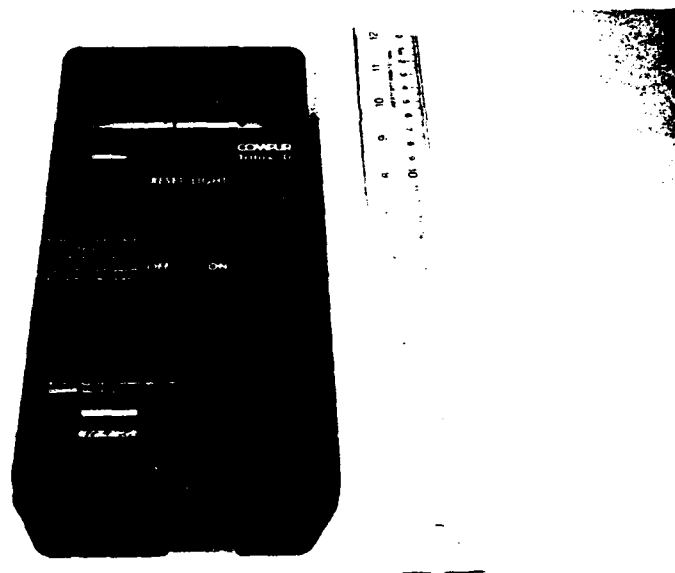
FIGURE 34. Compur Tritox D/M (Miles, Inc., Houston, TX).
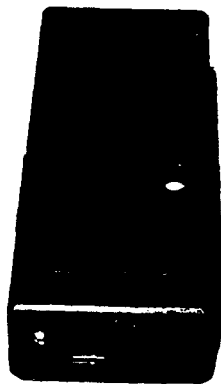
FIGURE 35. MiniGas (Neotronics of North America, Inc., Gainesville, GA).
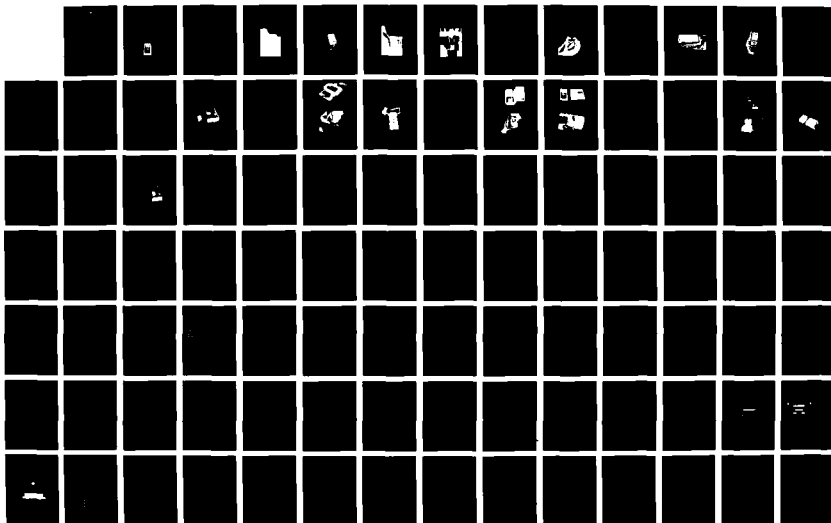
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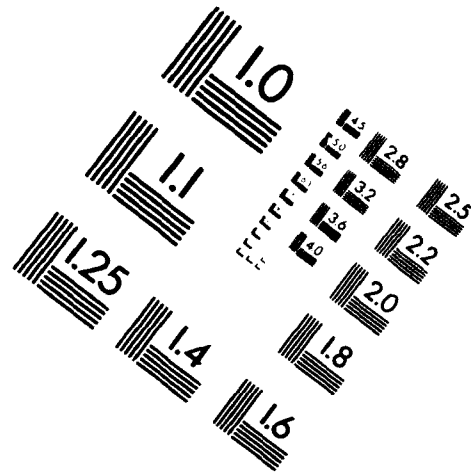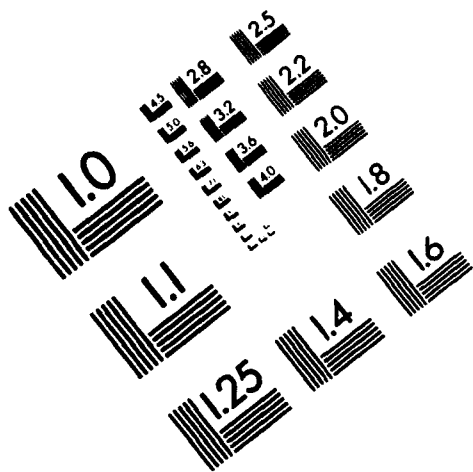
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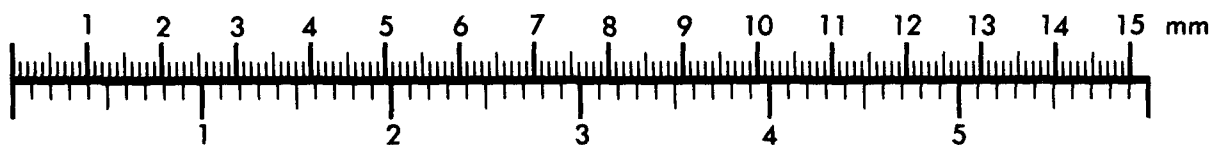
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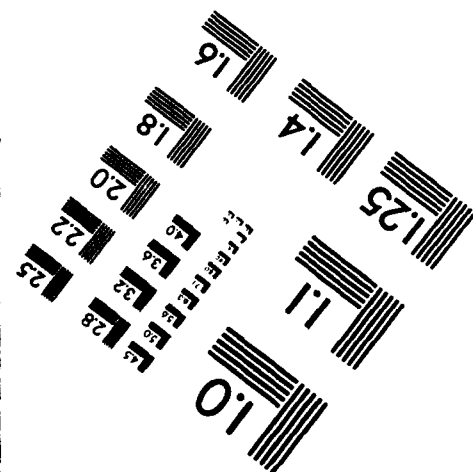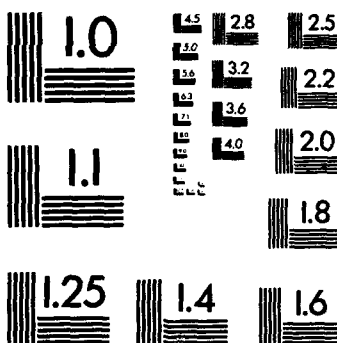
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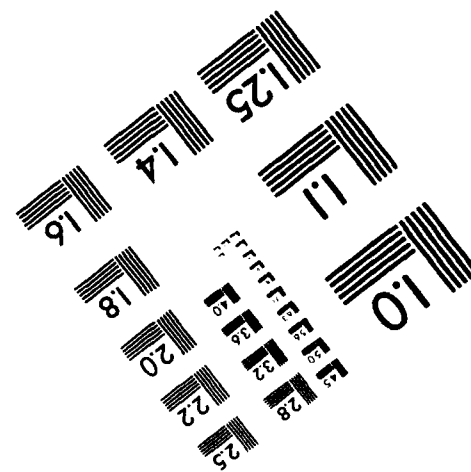
FIGURE 36. Scott-Alert Model S108 (Scott Aviation, Lancaster, NY).

In terms of portability and the convenience of carrying the monitor unattended during use, the major factors to consider are the size and weight of the meter. In general, bare meters which are small and light enough can simply be clipped onto a belt (Fig. 37) or carried using a wrist strap (Fig. 38). For added protection (to avoid damage to the device when banged on a hard surface), the bare monitor can be encased in a leather carrying case and worn on a belt loop as in Figures 37 and 39. From the authors' perspective, the most convenient way of carrying personal multigas meters is on the belt which offers minimum restriction of movement and shifting of the portable meter during normal use. The latter property is important especially during work involving a lot of movement. Note that among the monitors evaluated, only the HMX271, S108, MiniGas and PhD are small enough to be attached conveniently to a belt. Bigger and heavier multigas monitors are in general carried using a neck strap attached to the bare or encased instrument (as shown in Fig. 40). Using a neck strap, however, is not as convenient as having the meter attached to the belt especially during work involving a lot of crawling, and going up and down ladders.
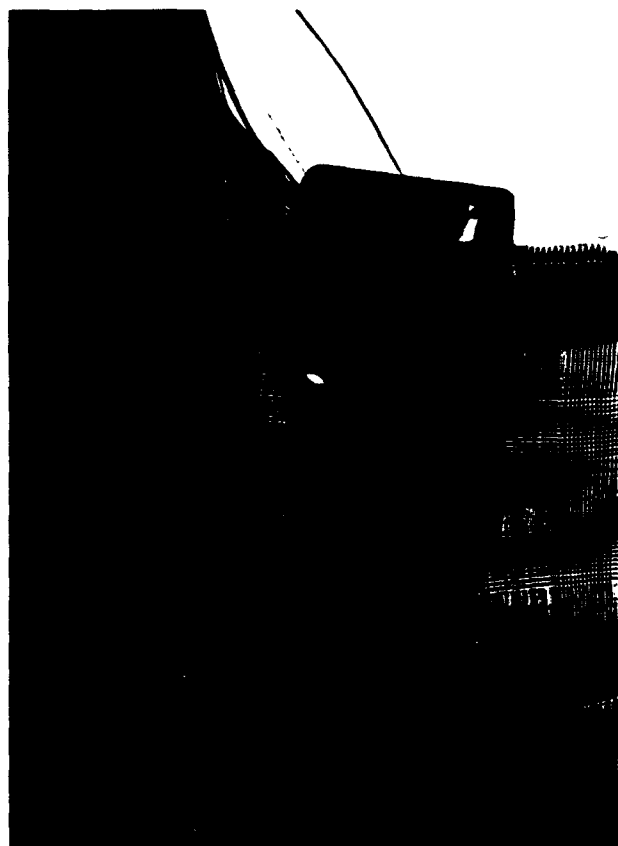
FIGURE 37. MiniGas monitor clipped onto a belt.

FIGURE 38. Wrist strap for the HMX271.
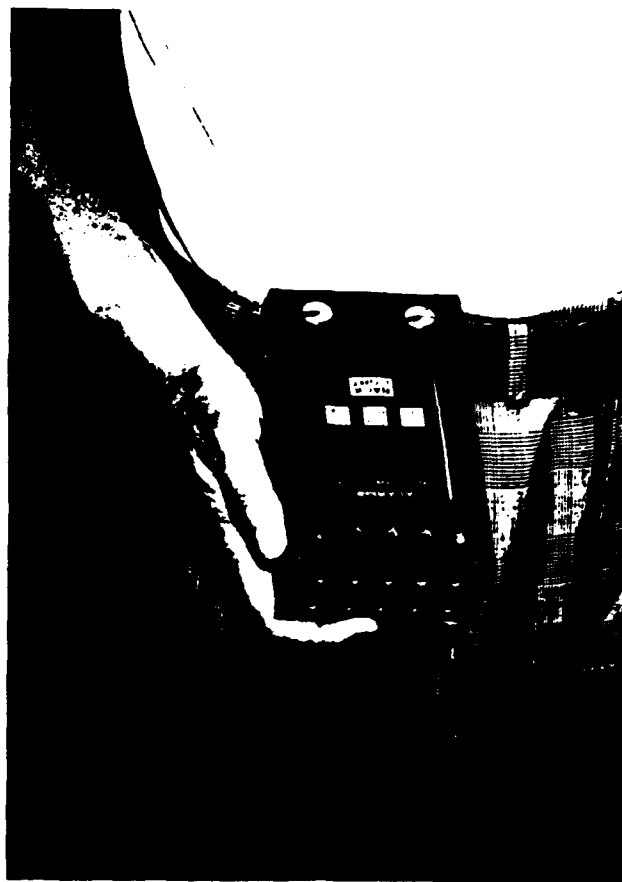
FIGURE 39. HMX271 enclosed in a leather carrying case for added protection, worn using a belt loop.

FIGURE 40. PhD monitor with vinyl case worn using a neck or shoulder strap.

3. Ease of Operation and Maintenance

a. Switching On and Off

In general, turning the monitors on and off for normal operation is a very simple task. Determining how to switch on the instrument is obvious for the S108, G700, Compur Tritox D, Compur Tritox M and CGM929A since the procedure simply involves sliding or pushing a clearly labeled switch or button. How to power the meter is, however, not that obvious for the PhD, MiniGas, CGS-80 and CGS-90, and may require reading the manual. The HMX271 is the most difficult instrument to turn on intuitively since switching on this device involves loosening a knurled nut that holds the calibration cover, rotating the cover by 180°, then locking it in place (Fig. 42).

More important than the ease of how to switch the monitor on and off, however, is the ability of the meter to inform the worker that the device is still in the monitoring mode (even in a safe environment) without the need for the worker to look down at the display. The latter property is important since it assures the worker that the meter has not been accidentally turned off during use. Note that without any alarms triggered, especially in an enclosed environment that has been determined safe during pre-entry evaluation, the worker generally assumes that a silent monitor means that the enclosed atmosphere is still safe to work in. Of the ten monitors evaluated, <u>only the MiniGas, G700, CGS-80 and CGS-90 periodically inform the user that the meter is in operation</u>. Both the MiniGas and G700 emit an audible bleep or alarm accompanied by a short flash of the alarm light periodically (i.e., every 10 seconds for the MiniGas, and every 60 seconds for the G700) during normal operation. For the CGS-80 and CGS-90, however, the red LED blinks once every 8 seconds during normal use. The CGS-80 even has an accompanying quiet chirp during the blinking of the alarm light.

Finally, although the HMX271 does not possess any ability to assure the user periodically that the meter is in operation during use, the on/off cover plate is locked in place during operation. Additionally, to prevent accidental shutdown, the on/off switch of both the PhD and CGM929A has a 3-second turn-off delay; while the MiniGas requires depressing two buttons simultaneously, aside from the time delay feature, to switch the monitor off.

FIGURE 41. HMX271 with calibration cover rotated by 90° from either off or on position.

b. Displaying Gas Levels During Normal Operation

All but two of the monitors studied provide a digital display of the target gas levels in the atmosphere. The two exceptions were the CGS-90, which provides a numerical readout for O_2 and a digital bar graph for combustible and toxic gases, and the CGS-80, which uses bar graphs for two of the three gases. Table 2 gives a list of which models gives a simultaneous display of all gas concentrations. As can be seen, of the ten models evaluated only three models (i.e., PhD, CGM929A and CGS-90) provide simultaneous gas readouts (e.g., as in Fig. 42). Note that the CGS-80 displays two gas concentrations simultaneously (i.e., a bar graph of the oxygen and either the combustible or toxic gas concentrations). The other instruments investigated display only one gas concentration at a time (see Fig. 43), although for the Compur Tritox D and Compur Tritox M models, the gas display cycles automatically among all gas readings. For the other monitors, which displays only one gas concentration at a time (i.e., HMX271, MiniGas, S108 and G700), the operator selects the gas that will be displayed. Regardless of whether simultaneous or individual gas concentrations are shown, all three gas concentrations are monitored continuously and simultaneously. All displays indicate which gas(es) have exceeded the pre-set level(s) during alarm conditions.

More important than the ability to display all gas levels being monitored simultaneously, however, is whether or not the monitor has a peak hold function that maintains the highest and the lowest oxygen concentrations, and the maximum levels of combustible and toxic gases encountered. Only four models — the PhD, CGM929A, MiniGas, and S108 — have peak hold functions. The peak hold capability is important during pre-entry area monitoring wherein the entire monitor is placed into the enclosed atmosphere. During such procedures, without peak hold capability, the reading will reset to safe values when the monitor is removed and passes through clean air outside or at the top of the confined space. This capability also proves useful if the exposure to "unsafe" air is transient.

FIGURE 42. Simultaneous digital display of all three gas concentrations for the PhD
meter.

FIGURE 43. Example of a single gas level display for the HMX271. Note the three gas
select switches located just below the display.

Table 15.   Monitors with peak hold functions and latching alarms.

Model	Hold or Peak Function ?[a]	Latching Alarm?[b]
PhD	Yes	No
CGM929A	Yes	No
CGS-80	No	No
CGS-90	No	No
G700	No	Yes
HMX271	No	No
Compur Tritox D	No	No
Compur Tritox M	No	No
MiniGas	Yes	Yes
S108	Yes	Yes

[a] Hold or peak function allows the instrument to display only the lowest and highest oxygen, the highest % LEL combustible gas, and the highest ppm toxic gas encountered.

[b] Latching or lock-on (or locking) alarms are alarms which can only be cancelled by the operator by pushing a switch. Hence, the alarm will not turn off automatically in "clean" air.

An alternative to peak hold function is incorporation of a latching, lock-on or locking alarm which can only be cancelled by the operator through the push of a button. Hence, when the lowered meter encounters unsafe levels of the target gas(es), the alarm is triggered and stays on until silenced by the worker. The disadvantage of latching alarms over peak hold functions is that the worker will not be able to measure quantitatively the target gas concentration in the confined space. Only the G700, MiniGas and S108 have latching alarm capabilities. Hence, only the MiniGas and S108 have both peak hold capability and latching alarms. Therefore, only the PhD, CGM929A, G700, MiniGas and S108 could be used for pre-entry enclosed area monitoring by lowering the entire monitor into the confined air. For the CGS-80, CGS-90, HMX271, Compur Tritox D and Compur Tritox M, confined space pre-entry evaluation must be by remote air sampling with a motorized or manual pump.

c. Ease of Servicing and Maintenance

The major factor which determines the ease of servicing and maintenance for the gas monitors is the sophistication of the microprocessor circuitry and software installed in the system. The sophisticated electronics simplify sensor calibration and setting of alarm points, while providing for automatic self-diagnostic checks. These self-diagnostic checks alert the user if the battery needs recharging or replacement, or if the sensors need recalibration or replacement. Finally, sensor calibration and alarm point setting can simply be carried out using menu-driven procedures and membrane switches or keys, although some instruments still require the operator to turn potentiometers with a screwdriver. Although the use of potentiometers may be operationally more difficult to perform, especially if the instrument case has to be opened, the procedure is still very simple and straightforward.

Sensor Zeroing And Span Calibration. Zeroing the sensor reading is the easiest calibration procedure to perform. The only precaution is that the process should be done in clean air since in general the sensors may respond to a number of volatiles, including those found in perfumes or after-shaves. Hence, the O_2 response is set to 20.9%, the combustible gas response to 0% LEL and the toxic gas response to 0 ppm. Table 16 outlines whether switches or potentiometers are used to adjust the zero setting of the monitor. In general, zeroing is more conveniently carried out using switches, although turning potentiometers to bring the response to the required values is also simple to perform since all of the potentiometers, like the membrane switches, are located outside the instrument case and hence are readily accessible.

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Table 16. Controls for zero, span and alarm point settings.

Model	What To Adjust For Zeroing, Span Calibration And Alarm Point Setting
PhD	Switches
CGM929A [a]	Switches
CGS-80 [b, c]	Potentiometers
CGS-90 [b, c]	Potentiometers
G700	Switches
HMX271	Potentiometers
Compur Tritox D	Switches [d]
Compur Tritox M	Switches [d]
MiniGas	Switches
S108 [e]	Potentiometers

[a] For the CGM929A, both switches and potentiometers are used to perform the zeroing and span calibration procedures. Note, however, that turning potentiometers using a screwdriver are necessary only if the current gas concentration displayed has gone out of range of the capacity of the membrane switch to do the calibration automatically.

[b] Adjusting the % O_2 setting for the CGS-80 and CGS-90 is done by turning a knob conveniently located outside the case.

[c] Only the zeroing of the O_2 response (wherein the reading is set to 20.9% O_2 in clean air) can be done for the CGS-80 and CGS-90.

[d] The Compur monitors were the only meters investigated with numeric keypads which allow the operator to type in directly desired numerical values. For all the other monitors (i.e., with switches and potentiometers), adjusting the current numerical setting displayed is accomplished by incremental addition or subtraction.

[e] Similar to the CGM929A, zeroing of the S108 can be achieved using membrane switches and potentiometers. Adjusting the potentiometer setting, however, is used only when the current gas reading cannot be rezeroed automatically using the membrane switch.

Zeroing of the instrument using switches involves pressing one to three switches simultaneously or consecutively. For example, to zero the PhD readings, one simply depresses the 'cal' membrane switch twice (see Fig. 45), and zeroing is performed automatically. It should also be noted that for monitors which displays a single gas concentration at a time, the zeroing process will have to be done three times, once for each sensor.

Span calibration of the sensors, on the other hand, involves exposure of the different sensors to standard gas mixtures followed by resetting of the displayed numerical values to the standard concentrations after equilibration. The procedure is carried out conveniently using a set-up similar to that shown in Fig. 1 for the CGM929A wherein the calibration gas (containing known concentrations of O_2, CH_4, and H_2S in a compressed gas cylinder) are flowed directly to the sensor housing enclosed by the calibration cup or cover. This set-up is easier and quicker to use than the calibration set-up used in the study (Fig.2).

Finally, similar to that of the zeroing protocol, span calibration is easier to perform for monitors with membrane switches rather than potentiometers. However, the directions on how to carry out span calibration of the sensors is simpler for monitors wherein potentiometers have to be turned. The only possible major problem is using potentiometers is physically locating where and which they are. Adjustments for the CGS-80 and CGS-90 are particularly inconvenient. The potentiometers are located inside the device, requiring that the instrument case be opened first (see Fig. 45). Furthermore, the labels can only be found in the instruction manual. The HMX271 has a cover with labels for the potentiometers, but it must be rotated by 90° from the ON/OFF position (Fig. 41). For the S108, the necessary potentiometers are located at the back side of the meter, and unlike the CGS-80, CGS-90 and HMX271, are clearly labelled. For the HMX271, the labels are written on the calibration cover. For those with membrane switches, span calibration can be a very involved process and may require reading the instruction manual more than once. The major difficulty in using switches is determining how to get to the calibration mode, and how to incrementally increase or decrease the current displayed values. For example, getting to the span calibration mode for the G700 involves depressing and holding the gas select key (i.e., either O_2, H_2S or CH_4) followed by turning off then on the meter. Once in the calibration mode, the displayed numerical value is decreased by depressing the 'EX' key, and increased by depressing the 'OX' key (see Fig. 46).
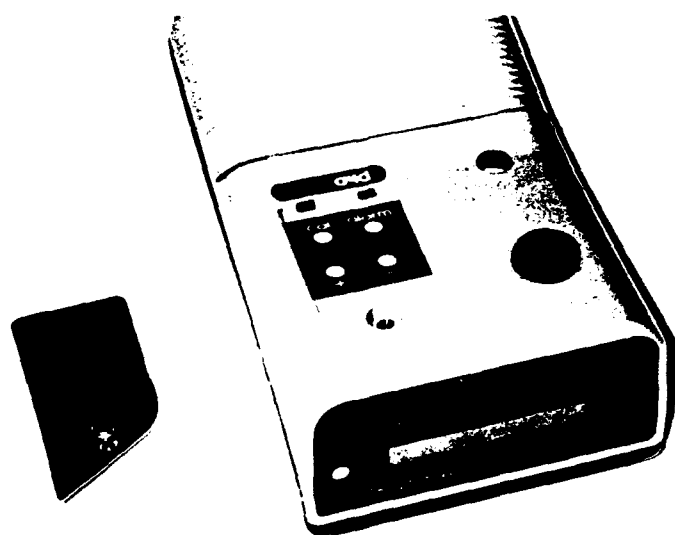
FIGURE 44.   Calibration adjustment switches for the PhD meter. Note the cover (or access panel) of these switches on the left part of the picture.

Checking And Adjusting Alarm Settings. In general, adjusting the alarm setting is a more complicated procedure than calibrating the sensors. Ease of adjustment for alarm points may not be a principal concern, as they are usually fixed by regulatory or conventional industrial hygiene guidelines, and once set may not routinely be changed. The applicable concentration ranges for resetting the respective alarm points can be seen in Table 17. It is emphasized, however, that proper use of the table requires considering the manufacturer-suggested applicable concentrations ranges for the meters as indicated in Table 2. Finally, note that the ranges given in Table 17 were obtained experimentally by determining the minimum and maximum limits of the different switches and p   meters (and numerical keypads for the Compur Tritox D and M) necessary to adjust the ..arm points.

As with span calibrations, adjusting alarm points is easier to accomplish for meters with membrane switches (see Table 16), although the step-by-step procedure will be more complicated. In all monitors employing potentiometers (CGS-80, CGS-90, HMX271 and S108), the applicable potentiometers are all located inside the main body of the instrument. Hence, adjusting the current alarm setting of the potentiometer while looking at the display can be a challenging task (see Figs. 45, 47 and 48). Additionally, every time the instrument case is opened, it is always possible to disconnect some of the wires inside the device. This happened once for the HMX271 Dry Cell during the course of this study. Again, the situation is worse for the CGS-80 and CGS-90 since the potentiometer labels can only be read from the instrument manual. Finally, it should be noted that all alarm points for the MiniGas are factory set and unchangeable since no directions are given in the manual on how to reset them; while the high O_2 alarm for the S108 is also fixed since the necessary potentiometer to be adjusted is glued in place. For the CGS-90, the combustible and toxic gas alarm points are set automatically at the same concentration as that of the span gas. Hence, if one desires a 10% LEL CH_4 or 10 ppm H_2S alarm setting for the combustible and toxic gas sensors, respectively, span calibration should be done using the same target gas concentrations. [See Appendix]

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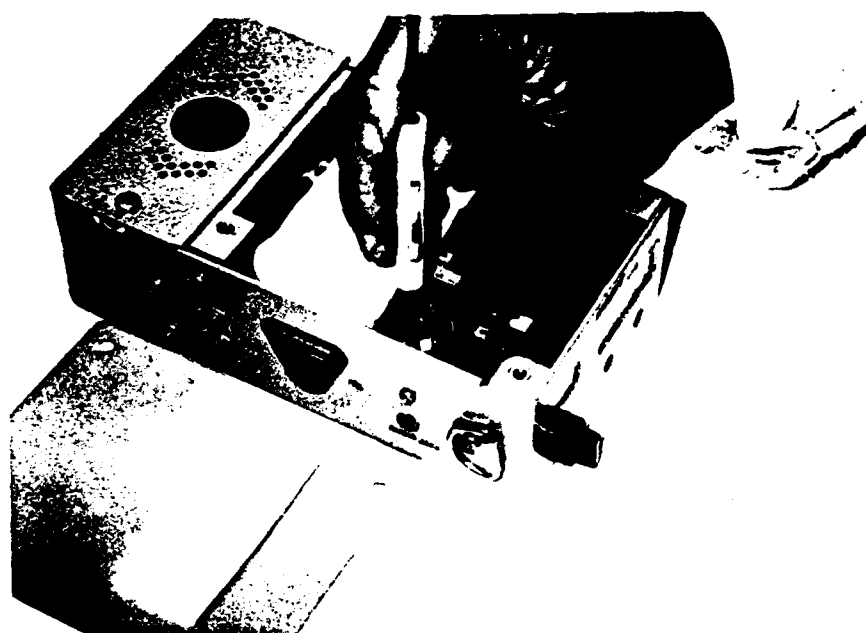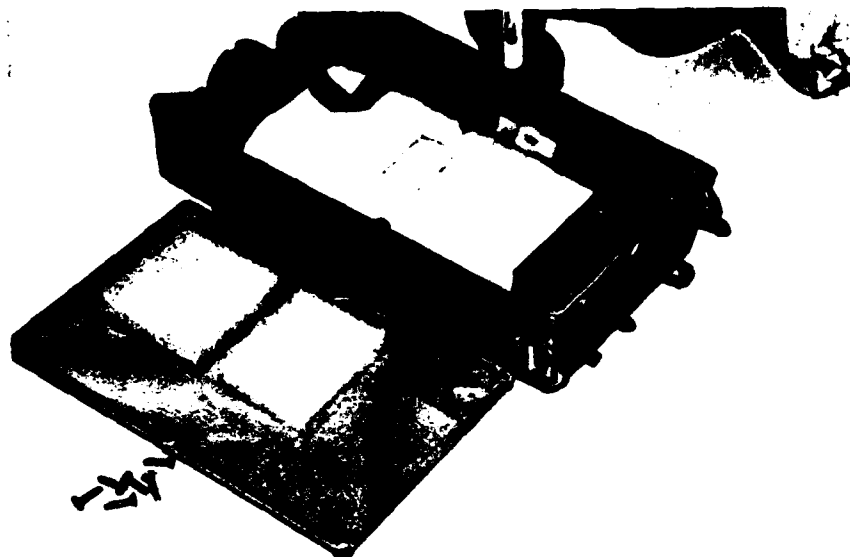
FIGURE 45.   Adjustment of calibration and alarm potentiometers for the CGS-80 [Top] and CGS-90 [Bottom] monitors. Note the instrument cover plate on the left portion of the illustrations.

FIGURE 46.   Gas select switches for the G700. The 'EX' switch is for the % LEL of explosive gas, the 'TOX' switch is for ppm of toxic gas, and the 'OX' switch is for % oxygen.

Table 17.Applicable concentration ranges for setting alarm points.

Model (SN) [a]	Concentration Range For Setting Alarm Points[b]			
	Low O$_2$ (%O$_2$)	High O$_2$ (%O$_2$)	% LEL CH$_4$	ppm H$_2$S
PhD (DK108-1428)	As low as 0.0	Up to 100.0	0.0-3276 [c]	0.0-3276 [c]
PhD (DK108-1429)	As low as 0.0	Up to 100.0	0.0-3276 [c]	0.0-3276 [c]
CGM929A (4571)	17.0-20.9	20.9-25.5	1-50	1-120
CGM929A (4572)	17.0-20.9	20.9-25.5	1-50	1-120
CGS-80	As low as 16.5	None	10 and 20	10 and 20
CGS-90	As low as 18.4	Up to 31.0	10 and 20	10 and 20
G700 (91090289)	15.0-20.9	None	10-80	1-20
G700 (91090290)	15.0-20.9	None	10-80	1-20
HMX271(NiCd)	As low as 0.0	Up to 43.3	0-124	0-95
HMX271(Dry Cell)	As low as 0.0	Up to 39.4	0-22	0-124
Compur Tritox D	As low as 0.0	Up to 99.9	1-99	0-999
Compur Tritox M	As low as 0.0	Up to 99.9	1-99	0-999
MiniGas(NiCd)	Fixed at 19.5	Fixed at 23.0	Fixed at 10	Fixed at 10
MiniGas(Dry Cell)	Fixed at 19.5	Fixed at 23.0	Fixed at 10	Fixed at 10
S108 (91361634)	18.1-25.0	Fixed at 25.0	0.0-57.0	0-73
S108 (91361656)	18.1-24.6	Fixed at 25.0	0.0-57.3	0-70

[a] SN = Serial Number.

[b] The concentration ranges given in this table should be used in conjunction with the applicable monitor concentration (or detection) ranges given in Table 2. For example, although the high O$_2$ alarm for the PhD has a limit of 100.0% O$_2$ as indicated in this table, a closer look at Table 2 reveals that based on manufacturer specification, the actual or practical highest % O$_2$ alarm setting that can be used is only 25.0% % O$_2$.

[c] For the PhD monitor, the incremental value for concentration was by 0.1 from 0.0 to 9.9, then by 1 up to 3276% LEL or ppm H$_2$S.
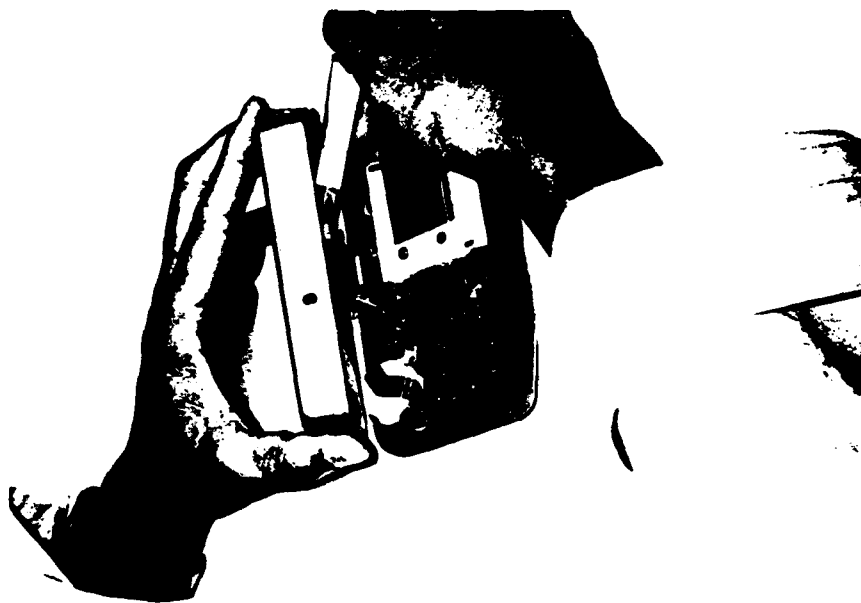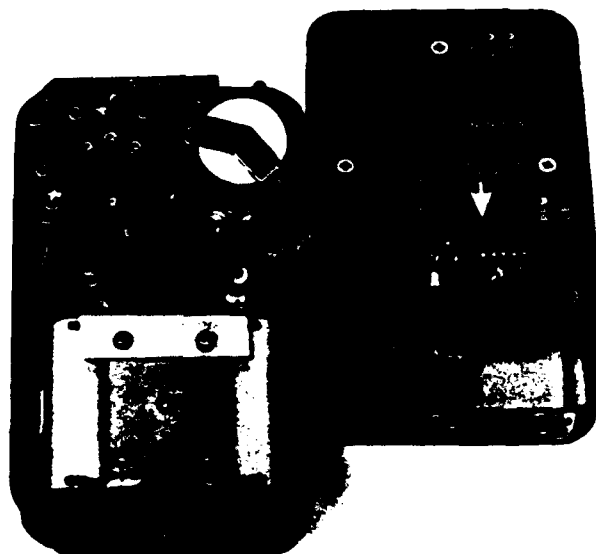
FIGURE 47. Open halves of the HMX271 personal monitor. The bottom diagram illustrates how fragile the circuitry is for resetting the alarm points since the appropriate potentiometer must be turned while looking at the gas level display.
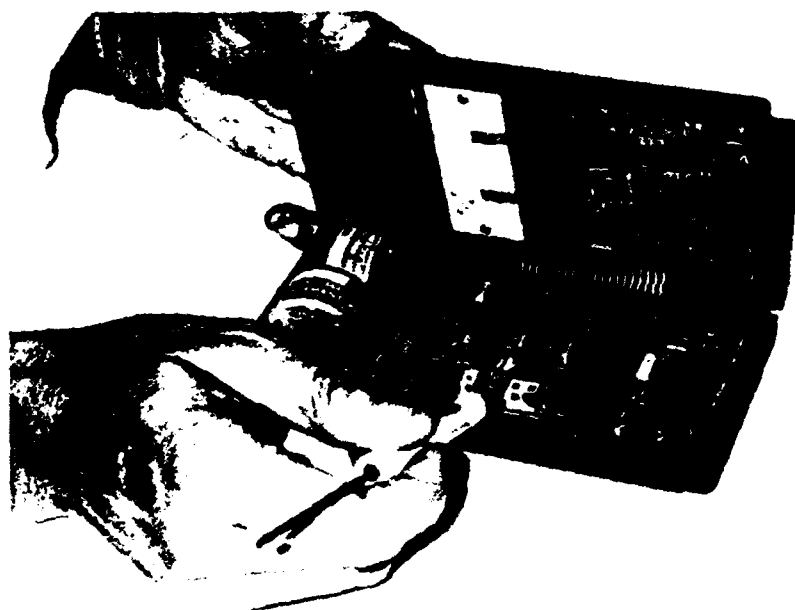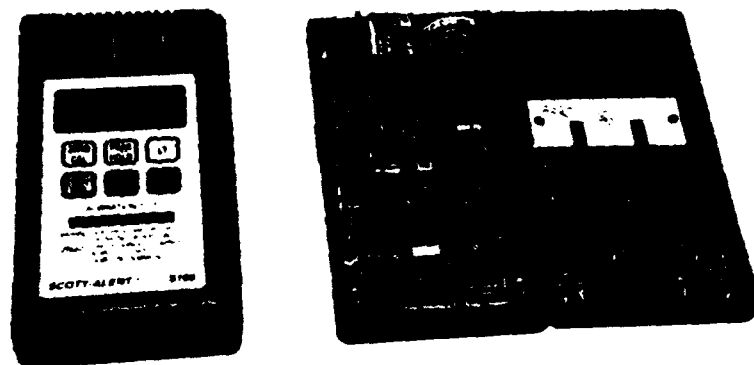
FIGURE 48. Open halves of the S108 monitor. The bottom picture shows how resetting of the alarm potentiometer is to be performed while the operator is looking at the digital display in the front panel.

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Charging And Replacing The Batteries. Personal multigas monitors are powered by either rechargeable NiCds or alkaline dry cells. Knowing when to charge the NiCd battery or replace the disposable dry cells is a simple task since all personal monitors have low-battery power warning alarms (both audible and visual). Once these alarms are triggered, the batteries should either be charged or replaced. If this is not done, the monitor automatically shuts down preventing permanent damage to the NiCd due to over-discharge, but more importantly preventing the monitor from providing wrong or unreliable gas readouts due to insufficient battery power. From Fig. 25, it can be seen that all the batteries used in personal meters supply at least 8 hours of continuous minimum operating time.

For recharging NiCds, either single chargers or multiple charging stations are available (Fig. 49). For example, multistation chargers are available for the HMX271 wherein up to twelve monitors can be recharged using only one 110V outlet. Finally, recharging can be done for an indefinite amount of time for all the chargers available since all of them automatically go to "trickle charge" when the battery has been fully recharged but left in the station.

More important than the recharging procedure is the availability of replacement battery packs which can instantly be connected to the monitor in the worksite. For dry cell-powered meters (HMX271 Dry Cell, MiniGas Dry Cell and CGM929A), the worker simply has to bring along extra alkaline batteries plus the necessary screwdrivers to open the battery case. For NiCd-powered devices, however, the situation is not that simple since for all of the NiCd-powered meters evaluated (PhD, CGS-80, CGS-90, G700, HMX271 NiCd, Compur Tritox D, Compur Tritox M, MiniGas NiCd and S108), only the CGM929A and MiniGas have easily detachable NiCd battery packs (Fig. 50). Hence, only for the CGM929A and MiniGas can one conveniently bring along fully-charged NiCd packs for field replacement.

Sensor Replacement. Determining when the sensors have to be replaced is not trivial. For safety reasons, one should know how old the sensors are, and they should be replaced before they become defective. Normally, the monitor has a mechanism for detecting when the sensor begins to fail or provide unreliable readings. However, a bad sensor signal does not always mean that the sensor needs to be replaced. During the study, only once did we do this procedure ourselves (for the O_2 sensor of both PhD meters as listed in Table 18). Hence, before replacing the sensor when the unit cannot be zeroed or be span calibrated,

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the recommended procedure is to first call the technical or service support department of the manufacturer.

Replacement of bad sensors is trivial. These sensors are very compact, and replacement simply involves opening the sensor compartment cover or the instrument case, unscrewing the wires and metal holders which keeps them in place, then pulling out the sensor (see Fig. 51). To install the new sensor, simply plug it in the the appropriate socket, then connect the necessary wires and metal sheet holders. All of the different O_2, H_2S and CH_4 sensors used have a finite operating life. For example, oxygen electrochemical cells normally last for only twelve months in air. Hence, with constant monitor use sensor replacement will eventually be necessary, and for safety reasons should only be performed by certified or qualified personnel. Marking each unit with the date to replace each sensor will ensure that the units will not suffer from an outdated sensor.
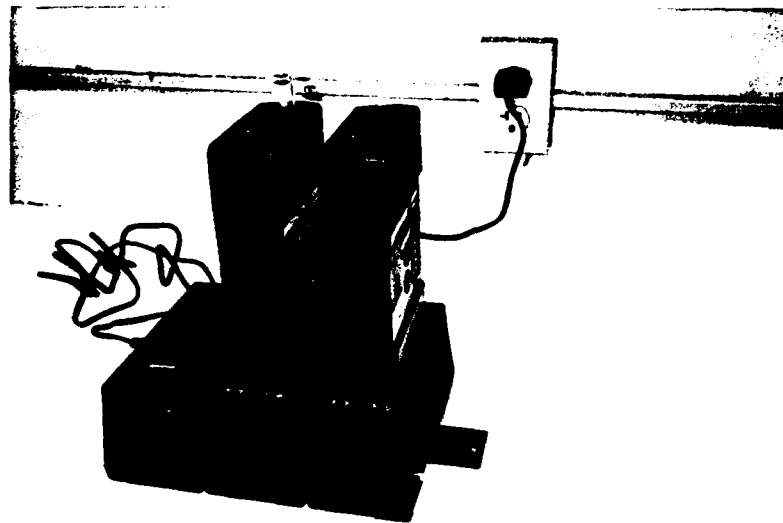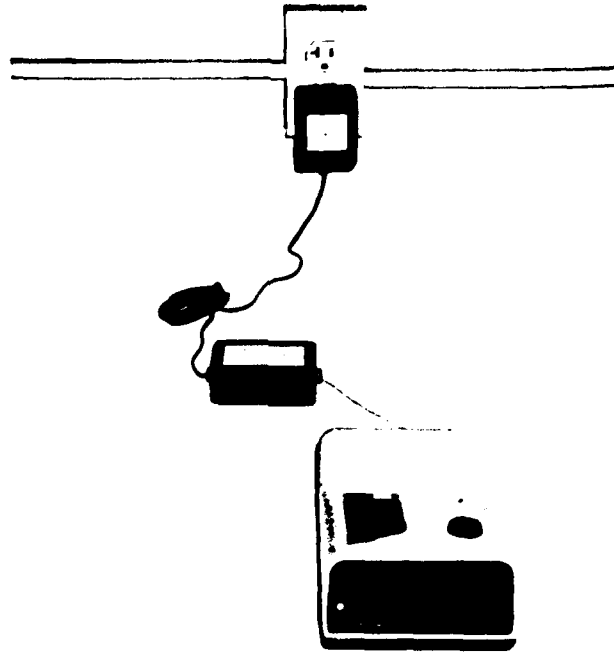
FIGURE 49.   Single NiCd charger for the PhD [Top], and multiple charging stations for the Compur Tritox D and M [Bottom]. Note that in both versions, only one 110V outlet is used.
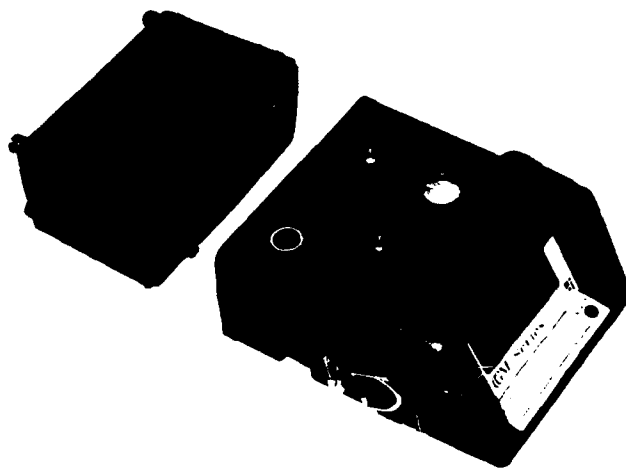
FIGURE 50. Detachable NiCd battery pack for the CGM929A. Note that the MiniGas also has a similar replaceable NiCd assembly.

d. Repair Record

A summary of the major repairs done to the meters evaluated is given in Table 18. Note that this list was limited only to repairs/part replacements performed/provided by the manufacturers. In general, no serious repair was necessary for any of the monitors, except those involving the membrane switches of the two PhD meters, and the display of the CGM929A #2. In both cases, however, repair turnaround time was less than two weeks (including mailing by overnight delivery). Replacement of the O_2 cells for both PhD's, and the O_2 and toxic gas cells for the HMX271 Dry Cell, however, was not a serious problem since they were required after already eight months of monitor use. Like all the repairs performed on the meters, all sensor replacement was done free of charge since they were still covered by the one-year manufacturer warranty, except the display repair for the CGM929A. In general, all the instrument parts including sensors are guaranteed for one year, except the three sensors of the MiniGas which were guaranteed for two years. Finally, in terms of availability of technical support, all support staff were always available and were easily contacted by phone. However, based on our experience, more support personnel are available for the CGM929A, HMX271 and MiniGas compared to those of the other monitors investigated.

e. Quality of Instruction Manual

In general, reading the supplied instruction manual is enough to understand fully how to operate the different personal monitors. In terms of the ease of understanding them, however, the instruction manuals can be ranked as follows:

Easy To Understand: **G700, HMX271 and S108;**
Moderate Difficulty: **PhD, CGM929A, Compur Tritox D,**
                            Compur Tritox M and MiniGas;
Difficult to Understand: **CGS-80 and CGS-90.**

Table 18.Repair record for the different multigas meters evaluated.

Model	Repairs Or Parts Replaced
PhD	•Replaced the oxygen electrochemical cells for both PhD monitors just 8 months after delivery. •Repair needed for the membrane switches of both monitors 11 months after delivery. The problem with it was that the meter automatically goes to the "Diagnostic Mode" when switched on, and remained stuck in that mode.
CGM929A #2	Repair needed for the wiring inside the display just 7 months after delivery. The problem was that no display can be seen although the monitor can be switched on and off. [a]
G700	•Missing instruction manual on shipment.
HMX271 (Dry Cell)	•Replaced oxygen and toxic gas electrochemical cells 9 months after delivery.
Compur Tritox D or M	•Missing battery charger power cord on shipment. •Repair to battery charger unit after initial use. This was necessary because the charger was unitentionally plugged to a 110V outlet with the charger set at 220V. [b]

[a] According to the repair service section of Dynamation, Inc., someone tried to gain access to the wiring inside the display, resulting in some wires being disconnected and a missing part. Although no one at LSU did that, IES was charged for the service since such repairs were not covered by the warranty (although the monitor was with us for only 6 months), .

[b] For the Compur Tritox charger, no warning was given in the instruction manual that a voltage selector was provided in the charger. Although the meter was shipped from Houston to LSU, the charger was set to 220V when received. When the repaired charger was received, it was again factory set at 220V.
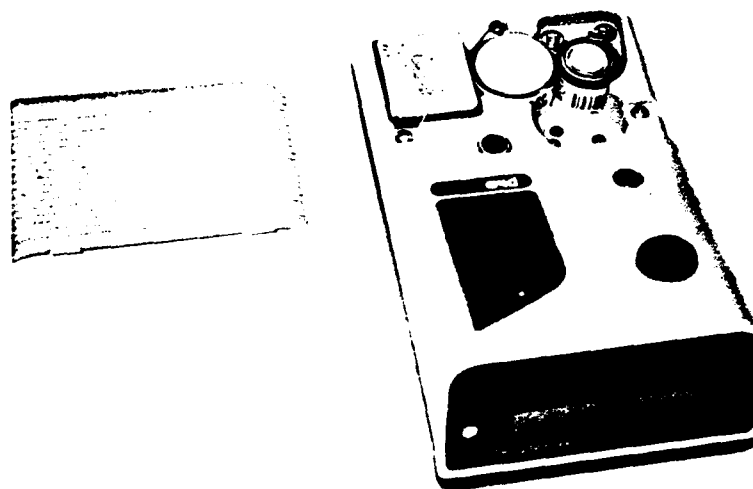
FIGURE 51. Chemical sensor compartment for the PhD meter. Note the sensor compartment cover used during sampling in the diffusion mode on the left side. As can be seen, the PhD monitor can accommodate a total of four gas sensors simultaneously. The picture only shows three sensors plus an empty fourth socket.

4. Cost

The government cost and current list prices to the general public (as of 20 July 1992) of the gas monitors evaluated can be seen in Table 19. It should be noted that all the monitors used in the study were ordered directly by the U.S. Coast Guard at approximately the same time, 15 August 1991, as shown in Table 20. Hence, the government prices indicated in Table 19 were the prevailing list prices during that period. Although it was not indicated in the Coast Guard-supplied price list for LSU as to which monitors were purchased on GSA (General Services Administration) schedule, based on the first author's correspondence with the suppliers, only the manufacturers of the HMX271 (Industrial Scientific Corp., Oakdale, PA) and MiniGas (Neotronics of North America, Inc., Gainesville, GA) are registered participants of the GSA program. The distributor of the G700 (GfG Gas Electronics, Inc., St. Louis, MO) did, however, give a 10% discount to the Coast Guard. Finally, to date the list prices for the HMX271 and S108 have increased slightly. More specifically, the GSA price for the HMX271 increased from $1139.00 to $1395.00, while that for the S108 (Scott Aviation, Lancaster, NY) increased from $1477.00 to $1521.00, from the date when these monitors were purchased by the U.S. Coast Guard. The price for the G700, however, decreased substantially during the same period from a unit price of $2570.00 (which does not include the charger which then cost $204.50) to $1899.00. Making the price reduction even more substantial is the fact that the current list price for the G700 now even includes the battery charger.

As can be seen from Table 19, the current list prices of the meters to the general public range from $995 for the MiniGas (Dry Cell) to $2290 for the Compur Tritox M. In general, those with data logging capability and more sophisticated software (e.g., PhD, CGM929A and G700) are more expensive. No generalizations can be made in terms of the prices and battery type employed. For example, the NiCd and dry cell versions of the HMX271 cost the same. For the MiniGas meter, however, the NiCd version cost $50 more than the dry cell version. The basic unit price of the CGM929A model of $1800 applies to the NiCd-powered device; the dry-cell powered monitor requires an extra dry cell battery case which currently costs an additional $140.65.

Generally, the NiCd-powered monitors will cost more since, except for the PhD, CGS-80, CGS-90 and G700, chargers or charging stations (an example of which can be seen in Fig. 50 for the Compur Tritox monitors) have to be purchased separately for these devices. In general, these single unit chargers can cost from $55.00 for the HMX271

compact charger to $185.00 for the MiniGas trickle charger. Finally, proper operation of the monitor will require the purchase of the appropriate calibration gas(es), and compliance with OSHA's new guidelines for work in confined spaces may necessitate the purchase of an optional sampling pump, if not already incorporated in the system.

The sensors used in the meters have a finite usable life. For mostr meters and with most sensors it is about 12 months. However, Dynamation (CGM) and Industrial Scientific Corp. (HMX) claim their oxygen sensors are good for 18 months, and their combustion detectors based on catalytic sensors may last up to 48 months.

This lead to an annual maintenance cost of $5-700 for replacement of sensors for each instrument, with the exception of Enmet which has a replacement cost of only $210 for all three sensors.

Table 19. Comparison of the government price when the monitors were purchased and current list price to the general public for the combination gas monitors evaluated. [a]

Model	Prices paid by CG[b] ($)	Current List Price ($) [c,d]
PhD [e]	1695.	1695.
CGM929A[f]	1800.	1941.
	2000[g].	—
CGS-80 [h]	736.	1095.
CGS-90 [i]	1395.	1395.
G700[j,k]	2313.	1899.
HMX271 (NiCd) [l]	1139.	1450.
HMX271 (Dry Cell) [l]	1139.	1450.
Compur Tritox D	1980.	1980.
Compur Tritox M	2290.	2290.
MiniGas (NiCd)	995.	1045.
MiniGas (Dry Cell)	945.	995.
S108	1477.	1521.

[a] Prices listed are for units with three sensors, including H_2S.

[b] Government prices listed were provided by the U.S. Coast Guard, except for the HMX271 models and the MiniGas models, which were GSA prices.

[c] These current list prices are for units to be purchased by the general public. Note, however, that quantity discounts may apply.

[e] Each PhD monitor is shipped with a carrying case with shoulder strap, belt clip, sample draw kit, battery and battery charger.

[f] The list price for the CGM929A is $1800.00, which already includes the standard NiCd battery pack. For the dry cell-powered monitor, using six size "C" cells, an extra dry cell battery case has to be purchased separately for $140.65, hence the $1940.65 list price.

[g] The second government price for the CGM929A includes a 0.6 cubic feet calibration gas, adaptor and flow regulator, and VHS training video tape.

[h] The CGS-80 monitor package includes the charger, carrying case and instrument manual. The instrument also came with below ground/public works calibration (i.e., with the MOS sensors calibrated for 10% LEL methane and 10 ppm hydrogen sulfide).

[i] The CGS-90 monitor package includes the charger, carrying case and instrument manual. The instrument also came with petrochemical calibration (i.e., with the MOS sensors calibrated for 10% LEL propane and 200 ppm methyl chloride).

[j] The government price for the G700 given does not include the charger, which when purchased by the U.S. Coast Guard cost $184.05. It should be noted that the government price given was 10% off the prevailing list price for the G700 and charger during purchase.

[k] GfG Gas Electronics reduced the list prices of the G700 and accessories effective January 1992. The current list price for the G700 package also includes the charger.

[l] Both the HMX271 (NiCd) and HMX271 (Dry Cell) are supplied with a leather carrying case.

[m] The current GSA list price for the HMX271 (NiCd) and HMX271 (Dry Cell) is $1395.00, which became effective last December 20, 1991.

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Table 20. Comparison of the receipt dates of the monitors - all ordered on 15 August 1991.

Model	USCG Order Date[a]	Date Received At IES[b]
PhD	08/23/91	08/31/91
CGM929A	08/26/91	09/03/91
CGS-80	—	11/13/91
CGS-90	—	11/13/91
G700	—	10/10/91
HMX271 (NiCd)	08/20/91	08/26/91
HMX271 (Dry Cell)	08/20/91	08/26/91
Compur Tritox D	08/20/91	11/01/91
Compur Tritox M	08/20/91	11/01/91
MiniGas (NiCd)	08/30/91	02/04/92
MiniGas (Dry Cell)	08/30/91	03/04/92
S108	08/22/91	09/19/91

[a] Note that the Minigas models were ordered before the first production models were available. Those received were among the first shipped.

[b] Although all the units were ordered by the U.S. Coast Guard, all the meters were shipped directly to IES at LSU.

IV. **EFFECT OF TEMPERATURE**

A. Methods

The standard test mixtures used to measure the steady-state meter readings and alarm response times at various temperatures were the following: 16 and 25% oxygen (O_2) in nitrogen; 30% LEL methane (CH_4) in air; and 35 ppm hydrogen sulfide (H_2S) in air. In determining the alarm response times, the low and high oxygen alarm points were set at 19 and 23% O_2, respectively. Similar values for the combustible and toxic gas sensors were set at 10% LEL CH_4 and 10 ppm H_2S, respectively. To determine the effect of temperature, the steady-state meter readings and alarm response times for each of the test standard gases were measured at -12°, 10°, room temperature (about 24°- 26° C) and 40° C. It should be noted that temperatures <-20° C are not recommended since the electrolyte solution in the electrochemical cells of the oxygen and toxic gas sensors freeze at these temperatures[22]. Prior to beginning the experiment, the gas monitors were turned on and allowed to warm-up in a clean, ambient laboratory air environment for at least 30 minutes. These were then zeroed in the same environment with the oxygen, toxic gas and combustible gas sensors set to 20.9% O_2, 0 ppm H_2S and 0% LEL (lower exposure limit) CH_4, respectively. The meter steady-state readings were determined by placing the monitors in a disposable inflatable glove bag (Model SS-30-20, Instruments for Research and Industry, 108 Franklin Avenue, Cheltenham, PA) containing an individual test standard gas, and letting the readings stabilize for at least five minutes before they were recorded. The alarm response times of individual multigas monitors were determined by exposing the gas monitor, with a preset alarm concentration for the particular standard, to a test standard gas placed in a model X-17-17 disposable glove bag (also from Instruments for Research and Industry) and timing the interval until the alarm went off., using a stop watch. These experiments were performed in a controlled temperature room that was equipped with coolers (Heatcraft Inc., Refrigeration Products Division, Atlanta, GA), heaters and thermometers. set at desired temperatures of -12°, 10°, room temperature (about 24°- 26° C) and 40° C, respectively.

B. Results

Tables 21 through 24 show the steady-state readings of the multigas monitors when exposed to test standards at various temperatures. From these data it can be seen that none of the multigas monitors that operate on alkaline dry cells (for example, CGM929A, Polytector G700, MiniGas, and the HMX271) functioned at temperatures of -12° C as the

dry cells failed, causing the respective multigas monitor power to switch off and not turn on. However, once these instruments were warmed to room temperature, they functioned normally. Both the Compur Tritox D and M also failed at this temperature resulting in a display message on its screen that read "T. out of range" indicating that the operational temperature was out of the instrument range. When first placed at -12° C for about four hours, the PhD monitors shut down and could not be turned back on even after they were equilibrated at room temperature and recharged. These were then sent back to the manufacturers who repaired them. At 10° the steady-state readings for a 16% O_2 standard ranged from 15.3-16.6%; for a 24.45% O_2 standard, the range was 23.5-25.2%; for a 30% LEL CH_4 standard the range was 26-40%; and for a 35 ppm H_2S standard, the range was 25-38 ppm. At room temperatures of 24°-26°C, the steady-state readings for a 16% O_2 standard ranged from 15.3-16.5%; for a 24.45% O_2 standard, the range was 24.3-25.6%; for a 30% LEL CH_4 standard the range was 26-44%; and for a 35 ppm H_2S standard, the range was 25-38 ppm. And at 40° C, the steady-state readings for a 16% O_2 standard ranged from 15.3-16.4%; for a 24.45% O_2 standard, the range was 23.9-25.7%; for a 30% LEL CH_4 standard, the range was 25-44%; and for a 35 ppm H_2S standard, the range was 24-39 ppm. Thus, all the multigas monitors showed good recognition of all the standard test gases without a significant difference in the recognition of the amount present at different temperatures. For all the multigas monitors that operate on rechargeable NiCd (nickel-cadmium) batteries (for example, PhD, CGS-80, CGS-90, HMX271, S108, and MiniGas), sample recognition was good at all the evaluated temperatures (except for the Compur Tritox D and M which could not function at -12° C), with standard deviations that varied from 0.1- 4.0%. It should however be pointed out that the variation in the meter steady-state readings was observed to be higher (standard deviations ranging from 1- 4%) during the monitoring of combustible gas (methane) and toxic gas (hydrogen sulfide), than during the monitoring of oxygen (standard deviations of 0.1- 0.3%). Furthermore, the CGS-80 and CGS-90 did not give steady-state readings for the combustible and toxic gases because the standard concentrations were high, resulting in the readings exceeding the instrument's maximum concentration range of 20% and 20 ppm for combustible and toxic gases, respectively. The S108, PhD, MiniGas and HMX271 monitors that use NiCd rechargeable batteries gave higher steady-state readings for 30% LEL CH_4 at -12° C than at 10°, 24° and 40°C.

Tables 25 - 28 show the results for the alarm response times, in seconds, of the various multigas monitors when exposed to various test gases. Alarm response time in this case was defined as the elapsed time from test gas exposure to the point when the alarm

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sounds. At -12° C, the alarm response times for oxygen deficiency, of the multigas monitors that operate using alkaline dry cells (CGM929A, MiniGas, and HMX271) could not be determined as these instruments shut off. The Compur Tritox D and M alarm response times could also not be determined at -12° C as these instruments were out of range while both the Polytector G700 monitors shut off. The NiCd rechargeable battery instruments (PhD, MiniGas, HMX271, CGS-80 and 90 and S108 all gave relatively higher response times at -12°C than at other temperatures. In general, at temperatures of 10°, 24°, and 40° C the alarm response times of individual monitors were not significantly different. In terms of ascending amount of time it takes for the alarm of various monitors to indicate oxygen deficiency, these can be ranked in the following order: HMX271 < PhD < MiniGas < S108 < CGS-80 and 90 = CGM929A < Compur Tritox D and M < Polytector G700 (that is , HMX271 being the fastest and G700 the slowest). It should be pointed out however that although the alarm point was set at 19 % O_2 for all other monitors, the MiniGas has a factory set O_2 alarm point of 19.5 % O_2, for oxygen deficiency.

The response times for excessive oxygen are shown in Table 26. As indicated in Table 26, using an alarm point setting for oxygen of 23%. These settings for the G700 and CGS-80 could not be determined as these monitors have no oxygen overabundance alarm point setting while the S108 monitors have a factory set oxygen overabundance alarm point of 25%. Again, the monitors that use alkaline dry cells shut off at -12° C while those that use NiCd batteries, had relatively higher response times than those at higher temperatures. In terms of quickness in signalling the oxygen overabundance defined as at 23%, the monitors can be ranked as: HMX271 > PhD > MiniGas > CGS-90 > Compur Tritox M > Compur Tritox D >CGM929A, the HMX271 gas monitor being the fastest. However, the large differences in the alarm response times for the two CGM929A monitors could have been due to one of them having lost its calibration. The alarm response times for the individual monitors that could be determined, did not vary very significantly at 10°, 24° and 40° C, although most of the response times at -12° C were significantly higher.

Tables 27 and 28 show the determined alarm response times for combustible (CH_4) and toxic (H_2S) gases. As seen on table 27, the combustible gas alarm response times for the rechargeable NiCd battery gas monitors (PhD, CGS-80 and 90, HMX271, MiniGas and S108) were higher at -12° C than at higher temperatures (except for PhD monitors which had lower values). The monitors that are powered by dry cells (including the G700 and Compur Tritox D and M monitors) could not be operated at -12° C, as this temperature was too low for these monitors. At 10°C, room temperature and 40° C, the combustible gas alarm response times decreased with increasing temperature for all the gas monitors except

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for both the HMX271, S108 and MiniGas (Dry cell) monitors where the response times did not vary as much with temperature. In ascending order, the overall alarm response times for methane can be ranked as follows: CGS-80 < HMX271 = CGS-90 < S108 < PhD < MiniGas (NiCd) = CGM929A < Compur D and M = G700 < MiniGas (Dry cell).

The alarm response times for the toxic gas (H_2S) are shown in Table 28. The response times for the MiniGas monitors could not be determined since alarm point for these instruments is factory set at 50 ppm H_2S. Those for the CGM929A, G700 HMX271 (Dry cell) and Compur Tritox D and M could not be determined at -12° C as the temperature was too low. The PhD, CGS-80 and 90, S108 and HMX271 (NiCd) monitors had rather large toxic gas response times at -12° C compared to higher temperatures. At 10°C, room temperature and 40° C, the alarm response times for all the monitors ranged from about 5 - 24 seconds and did not vary considerably with temperature. In ascending order, the overall alarm response times for toxic gas can be ranked as follows:

CGS-80 < S108 = HMX271 = CGM929A < Compur Tritox D and M < PhD < CGS-90 < G700.

Table 21   Effect of temperature on the steady-state reading of gas monitors during the monitoring of oxygen deficiency. [a, b, c]

| Model | SN | Meter steady-state reading for 16.08% O2 | | | |
		- 12° C	10° C	24° C [d]	40° C
PhD (1602)	DK108-1428	16.3 ± 0.1	15.6 ± 0.1	15.3 ± 0.1	15.3 ± 0.1
PhD (1602)	DK108-1429	16.3 ± 0.1	15.6 ± 0.1	15.3 ± 0.1	15.3 ± 0.1
CGM929A	4571	Switched Off	15.6 ± 0.1	15.9 ± 0.1	15.9 ± 0.1
CGM929A	4572	Switched Off	16.4 ± 0.1	16.3 ± 0.1	16.4 ± 0.1
CGS-80 [e]	5872	15.2 ± 1.1	16.2 ± 0.3	16.4 ± 0.3	16.7 ± 0.3
CGS-90	630	17.9 ± 1.9	15.9 ± 0.3	15.8 ± 0.3	15.7 ± 0.3
Polytector G700	91090289	Switched Off	15.9 ± 0.2	15.8 ± 0.2	16.0 ± 0.2
Polytector G700	91090290	Switched Off	15.9 ± 0.2	15.9 ± 0.2	16.2 ± 0.2
HMX271 (NiCd)	9106081-105	16.9 ± 0.2	16.3 ± 0.2	16.2 ± 0.2	16.1 ± 0.2
HMX271(DryCell)	9106084-034	Switched Off	16.3 ± 0.2	16.2 ± 0.2	15.6 ± 0.2
Compur Tritox D	2596	T. range	15.4 ± 0.3	16.0 ± 0.3	16.1 ± 0.3
Compur Tritox M	2688	T. range	15.3 ± 0.3	15.9 ± 0.3	16.0 ± 0.3
MiniGas (NiCd)	000375	16.6 ± 0.3	16.3 ± 0.2	15.9 ± 0.2	16.1 ± 0.2
MiniGas(DryCell)	000412	Switched Off	16.4 ± 0.2	16.0 ± 0.2	16.2 ± 0.2
S108	91361634	16.3 ± 0.1	16.6 ± 0.1	16.5 ± 0.1	16.4 ± 0.1
S108	91361656	15.5 ± 0.1	15.7 ± 0.1	15.8 ± 0.1	16.2 ± 0.1

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

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Table 22   Effect of temperature on the steady-state reading of multigas monitors during the monitoring of oxygen overabundance. [a, b, c]

Model	SN	Meter steady-state reading for 24.45 % O_2			
		- 12° C	10° C	24° C [d]	40° C
PhD (1602)	DK108-1428	23.1 ± 0.1	24.8 ± 0.1	25.1 ± 0.1	24.8 ± 0.1
PhD (1602)	DK108-1429	23.6 ± 0.1	24.9 ± 0.1	25.1 ± 0.1	24.7 ± 0.1
CGM929A	4571	Switched Off	24.7 ± 0.1	24.7 ± 0.1	24.7 ± 0.1
CGM929A	4572	Switched Off	24.3 ± 0.1	24.3 ± 0.1	24.3 ± 0.1
CGS-80 [e]	5872	24.0 ± 0.8	25.0 ± <0	25.0 ± <0	25.0 ± <0
CGS-90	630	27.5 ± 1.7	25.2 ± 0.3	25.6 ± 0.3	25.7 ± 0.3
Polytector G700	91090289	Switched Off	23.9 ± 0.2	24.5 ± 0.2	24.6 ± 0.2
Polytector G700	91090290	Switched Off	24.2 ± 0.2	24.7 ± 0.2	24.7 ± 0.2
HMX271 (NiCd)	9106081-105	24.7 ± 0.1	24.4 ± 0.2	24.5 ± 0.2	24.8 ± 0.2
HMX271(DryCell)	9106084-034	Switched Off	24.7 ± 0.2	25.1 ± 0.2	24.9 ± 0.2
Compur Tritox D	2596	T. range	23.5 ± 0.3	24.3 ± 0.3	24.4 ± 0.3
Compur Tritox M	2688	T. range	24.7 ± 0.3	25.5 ± 0.3	25.5 ± 0.3
MiniGas (NiCd)	000375	26.2 ± 0.2	24.6 ± 0.2	24.7 ± 0.2	24.7 ± 0.2
MiniGas(DryCell)	000412	Switched Off	24.8 ± 0.2	24.9 ± 0.2	24.9 ± 0.2
S108	91361634	26.3 ± 0.1	24.3 ± 0.1	24.4 ± 0.1	23.9 ± 0.1
S108	91361656	26.1 ± 0.1	24.5 ± 0.1	24.3 ± 0.1	23.9 ± 0.1

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

Table 23 **Effect of temperature on the steady-state reading of multigas monitors during the monitoring of methane.** [a, b, c]

| Model | SN | Meter steady-state reading for 30 % LEL CH_4 | | | |
		- 12° C	10° C	24° C [d]	40° C
PhD (1602)	DK108-1428	41 ± 2	38 ± 1	38 ± 1	38 ± 1
PhD (1602)	DK108-1429	44 ± 2	40 ± 1	41 ± 1	40 ± 1
CGM929A	4571	Switched Off	29 ± 1	30 ± 1	31 ± 1
CGM929A	4572	Switched Off	43 ± 2	44 ± 1	44 ± 2
CGS-80 [e]	5872	Off Scale	range		
CGS-90	630	Off Scale	range		
Polytector G700	91090289	Switched Off	35 ± 2	37 ± 2	38 ± 2
Polytector G700	91090290	Switched Off	38 ± 2	40 ± 2	41 ± 2
HMX271 (NiCd)	9106081-105	27 ± 2	26 ± 2	26 ± 2	28 ± 2
HMX271(DryCell)	9106084-034	Switched Off	26 ± 2	26 ± 2	28 ± 2
Compur Tritox D	2596	T. range	33 ± 3	34 ± 3	36 ± 3
Compur Tritox M	2688	T. range	34 ± 3	36 ± 3	40 ± 3
MiniGas (NiCd)	000375	29 ± 2	26 ± 2	28 ± 2	31 ± 2
MiniGas(DryCell)	000412	Sw. Off	28 ± 2	29 ± 2	33 ± 2
S108	91361634	47 ±4	32 ± 2	28 ± 2	25 ± 2
S108	91361656	38 ± 4	28 ± 2	27 ± 2	25 ± 2

[a] Standard methane gas mixtures used consisted of methane in air. The certified concentrations of methane in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the combustible gas sensor reading set to 0% v/v methane) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

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Table 24   Effect of temperature on the steady-state reading of multigas monitors during the monitoring of a toxic gas (hydrogen sulfide). [a, b, c]

Model	SN	Meter steady-state reading for 35.1 ppm H_2S			
		- 12° C	10° C	24° C [d]	40° C
PhD (1602)	DK108-1428	25 ± 1	32 ± 1	33 ± 1	33 ± 1
PhD (1602)	DK108-1429	26 ± 1	33 ± 1	32 ± 1	33 ± 1
CGM929A	4571	Switched Off	26 ± 1	25 ± 1	24 ± 1
CGM929A	4572	Switched Off	28 ± 1	27 ± 1	25 ± 1
CGS-80 [e]	5872	Off Scale			
CGS-90	630	Off Scale			
Polytector G700	91090289	Switched Off	38 ± 2	37 ± 2	35 ± 2
Polytector G700	91090290	Switched Off	33 ± 2	31 ± 2	28 ± 2
HMX271 (NiCd)	9106081-105	23 ± 2	25 ± 2	26 ± 2	27 ± 2
HMX271 (DryCell)	9106084-034	Switched Off	25 ± 2	26 ± 2	26 ± 2
Compur Tritox D	2596	T. range	28 ± 3	28 ± 3	28 ± 3
Compur Tritox M	2688	T. range	38 ± 3	38 ± 3	39 ± 3
MiniGas (NiCd)	000375	38 ± 2	35 ± 2	35 ± 2	34 ± 2
MiniGas(DryCell)	000412	Switched Off	38 ± 2	37 ± 2	37 ± 2
S108	91361634	27 ± 2	30 ± 2	33 ± 2	27 ± 2
S108	91361656	34 ± 2	34 ± 2	36 ± 2	32 ± 2

[a] Standard hydrogen sulfide gas mixtures used consisted of hydrogen sulfide in air. The certified concentrations of hydrogen sulfide in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA).

[b] The meters were zeroed (i.e., the toxic gas sensor reading set to 0% v/v hydrogen sulfide) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

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Table 25   Effect of temperature on the response time of multigas monitors during the monitoring of oxygen deficiency. [a, b, c]

Model	SN	Meter response time, in seconds, for 16.08 % O_2 (Alarm at 19% O_2)			
		- 12° C	10° C	24° C[d]	40° C
PhD (1602)	DK108-1428	2.9± 1.3	2.5 ± 0.8	2.6 ± 1.5	2.3 ± 1.2
PhD (1602)	DK108-1429	4.0 ± 1.8	3.4 ± 1.3	3.9 ± 1.0	3.4 ± 1.1
CGM929A	4571	Switched Off	9.9 ± 2.2	8.5 ± 3.8	10.5 ± 4.7
CGM929A	4572	Switched Off	20.9 ± 7.0	14.5 ± 4.9	16.6 ± 5.3
CGS-80 [e]	5872	28.9 ± 8.6	16.3 ± 0.4	16.1 ± 5.4	18.0 ± 6.0
CGS-90	630	4 2. ± 14.	13.9 ± 3.0	13.8 ± 3.6	12.5 ± 4.2
Polytector G700	91090289	Switched Off	26.8 ± 8.3	23.1 ± 7.4	21.5 ± 7.9
Polytector G700	91090290	Switched Off	26.4 ± 3.6	22.9 ± 6.7	21.3 ± 7.1
HMX271 (NiCd)	9106081-105	2.26 ± 1.21	1.8 ± 0.1	1.7 ± 0.5	1.5 ± 0.8
HMX271(DryCell)	9106084-034	Switched Off	1.7 ± 0.4	1.70 ± 0.4	1.3 ± 0.7
Compur Tritox D	2596	T. range	22.4 ± 8.7	19.0 ± 6.3	20.1 ± 6.5
Compur Tritox M	2688	T. range	20.6 ± 6.9	17.5 ± 5.8	17.9 ± 5.9
MiniGas (NiCd)	000375	7.6 ± 3.4	5.8 ± 0.7	5.8 ± 2.6	5.6 ± 2.6
MiniGas(DryCell)	000412	Switched Off	6.11 ± 2.29	6.53 ± 2.41	6.5 ± 3.4
S108	91361634	13.6 ± 4.5	9.2 ± 2.1	11.2 ± 2.7	8.4 ± 2.8
S108	91361656	13.7 ± 4.6	10.8 ± 2.62	12.8 ± 2.3	8.0 ± 1.7

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

Table 26   Effect of temperature on the response time of multigas monitors during the monitoring of oxygen overabundance.[a, b, c]

Model	SN	Meter response time, in seconds, for 25.45 % O_2 (Alarm at 23% O_2).			
		- 12° C	10° C	24° C[d]	40° C
PhD (1602)	DK108-1428	4.5 ±1.4	3.4 ±1.5	2.9 ±1.3	3.5 ±1.1
PhD (1602)	DK108-1429	5.4 ±2.2	3.3 ±1.5	3.2 ±1.3	4.1 ±1.7
CGM929A	4571	Switched Off	41.4 ±13.8	37.9 ±10.7	34.2 ±11.4
CGM929A	4572	Switched Off	170.3 ±42.5	130.3 ±22.5	104.8 ±26.4
CGS-80 [e]	5872	N/A	N/A	N/A	N/A
CGS-90	630	28.8 ±10.4	14.0 ±4.6	16.2 ±4.3	19.8 ±6.7
Polytector G700	91090289	N/A	N/A	N/A	N/A
Polytector G700	91090290	N/A	N/A	N/A	N/A
HMX271 (NiCd)	9106081-105	2.0 ±0.5	2.8 ±1.4	2.0 ±0.7	1.4 ±0.1
HMX271(DryCell)	9106084-034	Switched Off	2.7 ±1.3	2.1 ±0.5	1.8 ±0.4
Compur Tritox D	2596	T. range	40.1 ±13.4	35.1 ±9.6	31.0 ±10.4
Compur Tritox M	2688	T. range	30.7 ±10.2	24.2 ±8.1	23.9 ±7.9
MiniGas (NiCd)	000375	14.5 ±5.8	12.4 ±5.1	10.3 ±4.5	8.4 ±0.6
MiniGas(DryCell)	000412	Switched Off	6.4 ±2.4	6.0 ±2.3	5.5 ±2.5
S108	91361634	Factory alarm	point set at	25% Oxygen	
S108	91361656	Did not alarm	at this	concentration	

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

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Table 27   Effect of temperature on the response time of multigas monitors during the monitoring of combustible gas (methane).[a, b, c]

Model	SN	Meter response time, in seconds, for 30% LEL CH$_4$ (Alarm point at 20% LEL CH$_4$).			
		- 12° C	10° C	24° C[d]	40° C
PhD (1602)	DK108-1428	15.8 ± 7.1	18.5± 3.0	13.8 ± 6.2	9.0 ± 4.3
PhD (1602)	DK108-1429	14.0 ± 6.3	20.9 ± 3.8	13.3 ± 5.9	7.0 ± 3.2
CGM929A	4571	Switched Off	15.8 ± 7.9	14.6 ± 5.2	13.8 ± 6.9
CGM929A	4572	Switched Off	13.4 ± 7.1	13.3 ± 4.8	13.2 ± 6.6
CGS-80 [e]	5872	7.1 ± 3.5	3.2 ± 1.6	2.6 ± 1.0	2.3 ± 0.6
CGS-90	630	44.7 ± 22.3	7.2 ± 3.6	7.1 ± 2.9	6.7 ± 1.2
Polytector G700	91090289	Switched Off	20.1 ± 0.8	19.6 ± 5.0	18.1 ± 4.6
Polytector G700	91090290	Switched Off	18.7 ± 4.7	18.0 ± 3.6	17.9 ± 4.4
HMX271 (NiCd)	9106081-105	13.0 ± 5.5	6.6 ± 1.1	6.9 ± 3.1	9.8 ± 5.1
HMX271(DryCell)	9106084-034	Switched Off	7.1 ± 1.2	7.7 ± 3.9	10.0 ± 4.5
Compur Tritox D	2596	T. range	21.6 ± 7.85	20.0 ± 7.0	18.7 ± 8.2
Compur Tritox M	2688	T. range	15.6 ± 5.2	14.1 ± 4.3	12.1 ± 5.4
MiniGas (NiCd)	000375	31.1 ± 10.4	14.7 ± 1.3	13.7 ± 3.6	12.5 ± 4.1
MiniGas(DryCell)	000412	Switched Off	35.9 ± 5.3	36.5 ± 10.0	38.4 ± 12.8
S108	91361634	21.0 ± 7.4	9.7 ± 2.7	10.8 ± 4.9	11.6 ± 5.3
S108	91361656	17.5 ± 7.9	10.9 ± 2.6	11.0 ± 5.0	11.6 ± 5.2

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

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Table 28   Effect of temperature on the response time of multigas monitors during the monitoring of toxic gas (hydrogen sulfide). [a, b, c]

Model	SN	Meter response time, in seconds, for 35.1 ppm H$_2$S (Alarm point at 10 ppm H$_2$S).			
		- 12° C	10° C	24° C[d]	40° C
PhD (1602)	DK108-1428	38.1 ±12.7	13.14 ±2.0	14.6 ±3.2	16.0 ±5.0
PhD (1602)	DK108-1429	37.2 ±21.1	13.7 ±2.0	13.1 ±3.3	14.0 ±4.6
CGM929A	4571	Switched Off	11.6 ±2.5	9.2 ±2.0	9.1 ±2.3
CGM929A	4572	Switched Off	11.4 ±0.6	11.2 ±2.1	11.0 ±2.2
CGS-80 [e]	5872	26.0 ±7.1	5.3 ±1.4	7.7 ±1.9	9.8 ±2.4
CGS-90	630	140.3 ±41.0	24.9 ±12.0	19.4 ±2.6	18.4 ±2.1
Polytector G700	91090289	Switched Off	21.3 ±5.3	21.0 ±5.2	22.4 ±5.9
Polytector G700	91090290	Switched Off	22.8 ±5.6	23.2 ±4.6	24.0 ±5.9
HMX271 (NiCd)	9106081-105	14.43 ±7.11	7.7 ±1.2	10.5 ±4.2	13.9 ±6.9
HMX271(DryCell)	9106084-034	Switched Off	12.6 ±4.0	13.2 ±4.8	16.0 ±7.2
Compur Tritox D	2596	T.range	15.6 ±6.2	12.0 ±2.5	11.2 ±4.4
Compur Tritox M	2688	T. range	15.1 ±6.0	13.9 ±4.6	13.1 ±5.3
MiniGas (NiCd)	000375	Alarm point	factory set at	50 ppm H$_2$S	
MiniGas(DryCell)	000412	Switched Off	Alarm point	factory set at	50 ppm H$_2$S
S108	91361634	16.1 ±2.5	10.8 ±1.7	11.7 ±2.3	10.6 ±3.7
S108	91361656	16.6 ±2.8	9.3 ±1.2	10.7 ±1.8	11.0 ±2.8

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one week apart.

[d] 24° C = Room Temperature.

[e] The readout panel for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% increments.

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V. **EFFECT OF 100% RELATIVE HUMIDITY**

A. Methods

To monitor the effect of 100% relative humidity on detector response of the multigas monitors, the gas monitors were placed inside the test chamber containing the water-saturated test gas standard at 30° C. The standard test mixtures used were the same as those used to evaluate the effect of temperature. Similar to the previous procedure, the detector readout and alarm response times for the test standard gases were recorded for oxygen, combustible and toxic gas sensors. Relative humidities of 100% were achieved by bubbling the test gas through a flask of warm water while filling the test chamber. In this case, a model number 3310-40 hygrometer /thermometer (Cole-Parmer Instrument Company, Chicago, Illinois) was placed in the test chamber to monitor the humidity and temperature.

B. Results

Table 29 shows the oxygen steady-state meter readings obtained for the test standards. The steady-state readings at room temperature relative humidity (43-44%) were included for comparison. As indicated on Table 29, the steady-state readings for 16.08 and 24.45% oxygen standards were lower at 100% relative humidity, by 1-3%, than at 43-44% relative humidity for all the gas monitors except for the S108 gas monitors which gave very similar readings. However, the combustible and toxic gas steady-state readings, shown on table 30, show a much larger decrease at 100 % relative humidity that ranges from 6-27% for the combustible gas and an even larger decrease of 12-39% for toxic gas readings, for all the multigas monitors (except the CGS 80-and 90 monitors that gave out-of-range readings). It is also notable that the steady-state readings at 100% relative humidity decreased about twice as much for the toxic gas as compared to those for the combustible gas, for all the gas monitors, except for the S108 monitors where the decrease was similar.

Table 31 shows the oxygen alarm response time results for the various multigas monitors at 100% relative humidity. For all the monitors, the alarm response times at 100% relative humidity were found to be higher by 3-43% during the monitoring of oxygen deficiency and about 10-47% for oxygen abundance. Similar results for combustible and toxic gases (Table 32) are also higher by a range of 3-68% for combustible gas and to a larger extent of about 11-300% for toxic gas.

Table 29   Effect of 100% relative humidity on the steady-state reading of multigas monitors during the monitoring of oxygen deficiency and overabundance.[a, b, c, d]

Model	SN	Meter steady-state reading for oxygen deficiency and overabundance			
		16.08 % O_2		24.45 % O_2	
		RH = 43 %	RH = 100 %	RH = 44%	RH = 100%
PhD (1602)	DK108-1428	15.1 ± <0.1	14.8 ± 0.1	25.3 ± <0.0	24.8 ± <0.1
PhD (1602)	DK108-1429	15.1 < 0.1	14.8 ± 0.1	25.1 ± 0.1	24.7 ± <0.1
CGM929A	4571	15.9 ± 0.1	15.7 ± 0.1	24.7 ± 0.1	24.3 ± 0.1
CGM929A	4572	15.9 ± <0.1	15.7 ± 0.1	24.5 ± 0.1	24.2 ± 0.3
CGS-80 [e]	5872	16.2 ± 0.2	15.8 ± 0.2	24.8 ± 0.3	24.3 ± 0.3
CGS-90	630	15.7 ± 0.1	15.5 ± 0.1	24.8 ± 0.2	24.1 ± 0.2
Polytector G700	91090289	15.7 ± 0.1	15.4 ± <0.0$_1$	24.5 ± <0.0	24.1 ± 0.1
Polytector G700	91090290	15.8 ± 0.2	15.4 ± 0.1	24.5 ± 0.1	24.2 ± 0.1
HMX271 (NiCd)	9106081-105	15.7± 0.1	15.2 ± 0.2	24.7 ± 0.1	24.0 ± 0.1
HMX271(DryCell)	9106084-034	15.6 ± <0.1	15.3 ± 0.1	24.9 ± <0.0	24.4 ± 0.1
Compur Tritox D	2596	15.8 ± 0.1	15.3 ± 0.1	24.6 ± 0.1	23.8 ± 0.1
Compur Tritox M	2688	15.7 ± 0.1	15.0 ± <0.1	24.5 ± <0.0	23.9 ± <0.1
MiniGas (NiCd)	000375	15.6 ± 0.1	15.1 ± 0.1	25.1 ± 0.1	24.1 ± 0.1
MiniGas(DryCell)	000412	15.7 ± 0.1	15.2 ± 0.1	25.1 ± 0.1	24.3 ± 0.1
S108	91361634	16.0 ± <0.0	15.8 ± <0.1	24.3 ± <0.1	24.2 ± <0.1
S108	91361656	15.6 ± 0.1	15.6 ± <0.1	24.4 ± <0.1	24.4 ± <0.1

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one month apart.

[d] 100% relative humidity experiments were conducted at 30° C.

[e] The oxygen readout for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% oxygen increments.

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Table 30   Effect of 100% relative humidity on the steady-state reading of multigas monitors during the monitoring of combustible and toxic gases (methane and hydrogen sulfide). [a, b, c, d]

		Steady-state reading for methane and hydrogen sulfide			
		30 % LEL CH$_4$	30 % LEL CH$_4$	35.1 ppm H$_2$S	35.1 ppm H$_2$S
Model	SN	RH = 42 %	RH = 100 %	RH = 45%	RH = 100%
PhD (1602)	DK108-1428	31 ± 1	28 ± <0	35 ± 1	27 ± <0.0
PhD (1602)	DK108-1429	30 ± 1	27 ± 1	35 ± 1	27 ± <0.0
CGM929A	4571	36 ± 1	31 ± 1	23 ± 1	14 ± 1
CGM929A	4572	37 ± 1	32 ± 1	23 ± <0	14 ± <0
CGS-80 [e]	5872	Off Scale	Off Scale	Off Scale	Off Scale
CGS-90	630	Off Scale	Off Scale	Off Scale	Off Scale
Polytector G700	91090289	31 ± 1	28 ± 1	25 ± 1	18 ± 1
Polytector G700	91090290	32 ± 1	28 ± 1	24 ± <0	17 ± <0
HMX271 (NiCd)	9106081-105	30 ± 1	24 ± 1	34 ± 1	25 ± <0
HMX271(DryCell)	9106084-034	30 ± <0	26 ± 1	33 ± 1	25 ± 1
Compur Tritox D	2596	35 ± 1	29 ± 1	43 ± 3	30 ± 2
Compur Tritox M	2688	34 ± 3	29 ± 3	43 ± 5	30 ± 5
MiniGas (NiCd)	000375	31 ± 1	28 ± <0	28 ± <0	23 ± <0
MiniGas(DryCell)	000412	31 ± 2	29 ± 1	32 ± <0	28 ± <0
S108	91361634	30 ± <0	24 ± 1	35 ± 1	28 ± 1
S108	91361656	30 ± <0	22 ± 2	34 ± 1	25 ± 1

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one month apart.

[d] 100% relative humidity experiments were conducted at 30° C.

[e] The oxygen readout for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% oxygen increments.

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Table 31 Effect of 100% relative humidity on the response time of multigas monitors during the monitoring of oxygen deficiency and overabundance.[a,b,c,d]

Model	SN	Response time, in seconds oxygen deficiency and overabundance (% O$_2$)			
		16.08% O$_2$	16.08% O$_2$	24.45 % O$_2$	24.45 % O$_2$
		RH = 66%	RH = 100%	RH = 61%	RH = 100%
PhD (1602)	DK108-1428	2.8 ±0.5	3.4 ±0.4	8.4 ±0.5	11.4 ±0.8
PhD (1602)	DK108-1429	2.7 ±0.4	3.1 ±0.4	8.6 ±0.8	11.4 ±1.2
CGM929A	4571	29.3 ±1.7	33.6 ±1.8	107.8 ±28.8	118.4 ±5.9
CGM929A	4572	30.6 ±3.9	33.0 ±5.1	110.1 ±14.0	123.2 ±9.3
CGS-80 [e]	5872	2.8 ±0.2	3.6 ±0.5	N/A	N/A
CGS-90	630	37.4 ±2.9	48.8 ±6.9	50.9 ±5.0	58.2 ±3.9
Polytector G700	91090289	20.3 ±2.2	22.2 ±3.8	N/A	N/A
Polytector G700	91090290	23.6 ±2.8	26.4 ±1.2	N/A	N/A
HMX271 (NiCd)	9106081-105	1.4 ±0.2	1.5 ±0.4	2.4 ±0.2	3.6 ±0.9
HMX271(DryCell)	9106084-034	1.3 ±0.3	1.4 ±0.3	1.8 ±0.2	2.4 ±0.1
Compur Tritox D	2596	19.2 ±2.3	27.6 ±2.2	37.0 ±10.6	53.4 ±1.8
Compur Tritox M	2688	18.8 ±5.0	21.1 ±5.6	22.1 ±2.2	26.0 ±9.9
MiniGas (NiCd)	000375	5.4 ±0.4	5.6 ±0.4	10.3 ±0.6	14.7 ±2.3
MiniGas(DryCell)	000412	7.1 ±0.1	7.5 ±0.1	10.0 ±0.6	14.2 ±2.3
S108	91361634	11.1 ±0.5	11.5 ±0.7	NR	NR
S108	91361656	10.9 ±2.5	11.3 ±0.3	NR	NR

[a] Standard oxygen gas mixtures used consisted of oxygen in nitrogen. The certified concentrations of oxygen in the different mixtures were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the oxygen sensor reading set to 20.9% v/v oxygen) in clean ambient air.

[c] The different rows of data for each monitor model were obtained approximately one day apart.

[d] 100% relative humidity experiments were conducted at 30° C.

[e] The oxygen readout for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% oxygen increments.

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Table 32   **Effect of 100% relative humidity on the response time of multigas monitors during the monitoring of combustible (methane) and toxic (hydrogen sulfide) gases.** [a, b, c, d]

Model	SN	Meter response time, in seconds			
		30 % LEL CH$_4$	30 % LEL CH$_4$	35.1 ppm H$_2$S	35.1 ppm H$_2$S
		RH = 44%	RH = 100%	RH = 41%	RH = 100%
PhD (1602)	DK108-1428	8.6 ± 0.6	11.6 ± 0.7	14.5 ± 1.3	34.8 ± 5.3
PhD (1602)	DK108-1429	9.0 ± 0.7	12.0 ± 1.0	13.7 ± 1.0	32.1 ± 6.9
CGM929A	4571	10.9 ± 1.9	18.3 ± 2.2	9.7 ± 0.6	12.6 ± 1.0
CGM929A	4572	13.4 ± 2.5	18.7 ± 3.6	12.7 ± 0.5	15.0 ± 1.2
CGS-80 [e]	5872	4.2 ± 0.4	5.82 ± 0.22	14.8 ± 1.7	26.2 ± 2.6
CGS-90	630	7.5 ± 0.7	10.1 ± 1.1	21.9 ± 2.2	105.3 ± 30.0
Polytector G700	91090289	14.3 ± 1.0	16.7 ± 0.6	25.1 ± 4.7	27.7 ± 5.3
Polytector G700	91090290	13.8 ± 1.2	17.4 ± 0.8	27.5 ± 6.0	30.5 ± 5.7
HMX271 (NiCd)	9106081-105	11.0 ± 3.8	15.4 ± 5.4	7.5 ± 0.4	28.5± 18.3
HMX271(DryCell)	9106084-034	10.6 ± 3.0	12.4 ± 2.8	8.4 ± 2.7	25.5 ± 16.2
Compur Tritox D	2596	20.5 ± 2.8	27.6 ± 2.2	37.0 ± 10.6	53.4 ± 1.8
Compur Tritox M	2688	15.8 ± 2.1	21.1 ± 5.6	22.0 ± 2.2	26.0 ± 9.9
MiniGas (NiCd)	000375	9.5 ± 0.3	9.8 ± 0.7	NR	NR
MiniGas(DryCell)	000412	9.6 ± 0.6	10.3 ± 0.5	NR	NR
S108	91361634	21.5 ± 1.3	28.0 ± 5.3	10.4 ± 1.2	43.9 ± 3.9
S108	91361656	10.6 ± 1.3	13.8 ± 2.5	12.8 ± 0.5	48.9 ± 14.6

[a] Standard methane and hydrogen sulfide gas mixtures used were made in air. The certified concentrations were determined by an independent laboratory (Liquid Carbonic Specialty Gas Corporation, Baton Rouge, LA) using gas chromatography.

[b] The meters were zeroed (i.e., the combustible and toxic gas sensor readings were set to 0.0 % v/v) in clean, ambient air.

[c] The different rows of data for each monitor model were obtained approximately one day apart.

[d] 100% relative humidity experiments were conducted at 30° C.

[e] The oxygen readout for the CGS-80 is a bar graph ranging from 16.0 to 25.0 in 0.5% oxygen increments.

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VI. RUGGEDNESS/SURVIVABILITY

A. Methods

The effect of impact or shock on the performance of multigas monitors was evaluated because of the possibility that they may be dropped, banged onto walls or exposed to extreme weather conditions during their field use. Their performance during extreme weather conditions was evaluated in the previous sections on the effect of 100% relative humidity and temperature. Instrument ruggedness and survivability was evaluated as follows: A wooden swing arm measuring 6' x 3.5" x 0.75" was placed on top of a wooden support and connected at one end using a stainless steel hinge to provide a maximum angle of 180°. The support post was mounted vertically on a wall with the hinge at the top, leaving a clearance of about two feet from the floor. The mounting allowed the swing arm to be opened up to some known angle and released to strike the support attached to the wall. This arrangement allowed the instruments to be shock tested while controlling the orientation of the meters as they struck the solid surface. In order to conduct the shock trials for a particular monitor, the unit being tested was fastened at the lower end and outer side of the swing arm. The swing arm, with the gas monitor tied to it, was then lifted to a prescribed angle and allowed to swing freely so that it hit the support attached to the wall. The procedure was repeated for angles of 30°, 45° and 90°. This simulated the impact produced by accidentally banging the gas monitor on the wall or dropped onto a supported floor from heights of up to 6 feet.. To simulate the impact of falling to the cement floor, the swing arm carrying the gas monitor was made to strike a cement wall. The orientation of the gas monitor during release was based on the location of the display panel. Thus, for monitors with the display located on top when carried during usage (for example, the CGS-80, CGS-90, PhD, CGM929A, and MiniGas), the swing arm was released to hit the support post or cement wall with the display facing up. For the monitors with the display located in front during usage (for example, the Polytector G700, S108, HMX271, and Compur Tritox D and M) the swing arm was released to hit the support post or cement wall with the display side facing the support post or the wall. It is important to note that these monitors were shock tested without their leather casings, since these are sometimes used as shock absorbants. To observe the effect of the shock impact on the monitors, all the monitors were first zeroed in clean air and the steady-state readings of standards (16 and 25% oxygen (O_2) in nitrogen; 30% LEL methane (CH_4) in air; and 20 ppm hydrogen sulfide (H_2S) in air) monitored before and after impact. A summary of the effect of the impacts on the monitors is outlined below.

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B. Results

Impacting the multigas monitors at angles of 30°, 45° and 90° for at least once at each angle, with the swing arm striking on the wooden support post did not affect the standard steady-state readings of any of the gas monitors. When the swing arm was allowed to strike the cement wall, the monitors whose steady-state readings did not change after a total of six impacts each were the S108 and PhD monitors. The outer plastic shell of one of the Polytector G700 monitors broke after only one impact during which the instrument momentarily shut down and later resumed functioning normally. This particular G700 still functioned normally after two more impacts. The other G700 monitor functioned normally after one impact and was not subjected to further impacts.

The oxygen alarm for the HMX271 (Drycell) went off after just a single impact with the oxygen steady-state reading indicated as at 22.4% instead of 20.9% and started functioning normally after two minutes. After three additional impacts on the same monitor, the LCD display broke and the instrument stopped functioning. The LCD display for this instrument currently costs about $20.00 plus a separate charge for labor, according to the manufacturer (Industrial Scientific Corp., Oakdale, PA). The oxygen alarm for the HMX271 (NiCd) also went off after just a single impact with the oxygen reading indicated at 21.7% instead of 20.9%, and returned to normal after one minute. No further impacts were applied to this monitor.

The alarm for the MiniGas (Drycell) went off after a single impact with the oxygen (O_2), combustible gas (CH_4) and toxic gas (H_2S) readings indicated at 22.3%, 3% LEL and 2 ppm, respectively, instead of 20.9% O_2, 0% LEL CH_4 and 0 ppm H_2S. This monitor however, shortly reverted to normal and survived five more impacts. The MiniGas (NiCd) multigas monitor alarm also went off after only a single impact with the oxygen, combustible and toxic gas readings indicating 21.7%, 2% LEL and 2 ppm, respectively, instead of 20.9% O_2, 0% LEL CH_4 and 0 ppm H_2S. This monitor also shortly reverted to normal and survived five more impacts.

The Compur Tritox D monitor did not change its behavior after a single impact but failed to turn back on after three more impacts. According to the manufacturers of the unit (Miles, Inc., Houston, Texas), the shut down was caused by an integrated circuit (IC) unit that fell off on impact, as the unit functioned normally upon its restoration. The estimated cost for this repair was estimated by the manufacturers to be about $25.00. The Compur Tritox M survived a single impact and was not further subjected to another impact.

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Both the CGM929A monitors shut down momentarily and turned on after only a single impact. On subjecting one of them to further impacts, it shut down completely and could not be turned on, suggesting a possible electronic damage.

The CGS-80 monitor alarm went off momentarily after a single impact although the steady-state reading did not change. It however restored itself and was not subjected to further impacts. The CGS-90's alarm went off, after a single impact, with the oxygen reading at 21.8% and later restored itself. After two more impacts on the CGS-90, the power turned off and would not stay on except when held in the "Start" position. According to the manufacturers of the unit (Enmet Corporation, Ann Arbor, Michigan), the shut down was caused by an integrated circuit (IC) unit that fell off on impact, as the unit functioned normally upon its restoration. Due to similar complaints from other users about this IC unit falling off, the manufacturers have since started soldering this particular IC unit on the later models to prevent it from easily falling off.

VII. SUMMARY OF RESULTS

All of the meters investigated gave adequate linear sensor response and comparable selectivity over the practical concentration ranges for O_2, H_2S and CH_4. However, only the PhD and HMX271 had highly selective H_2S sensors which showed no response to CO, though those of the MiniGas and S108 exhibited only a slight response to CO.

Comparison of remote sampling capability among the monitors tested showed the G700 to be clearly superior in this parameter because its internal pump supplied a healthy sample flow rate. This instrument has another useful feature in that the operator can turn off the sampling pump to extend the operating time on a battery charge when diffusive sampling is sufficient. The sampling pump of the Compur Tritox M provided an insufficient flow for effective remote sampling. Neither was the Tritox M sample pump particularly effective in improving response time (over the diffusive mode) for local sampling. The other monitors may be available with external pumps, but expect these to add to the bulk and weight more than the internal pump of the G700.

In terms of accuracy of the sensor response to different H_2S and CH_4 test mixtures, most of the meters investigated gave accurate readings. The CGS-80, CGS-90, Compur Tritox D, and Compur Tritox M performed slighlty below the norm for combustible gas. All ten models, however, gave highly accurate readings for oxygen.

In selecting the best personal monitor to use of the ten models, the limiting criteria may be: alarm response time, portability, ease of operation and maintenance, and ruggedness. If alarm response time (together with accuracy of response) are the determining criteria, then the best monitor will be the HMX271, with the PhD, MiniGas and S108 models not far behind. For all three target gases analyzed, the HMX271 consistently gave the fastest alarm response times (2-7 seconds).

In terms of portability, the HMX271, S108, PhD, MiniGas and G700 weighed less than 1 kg, and the HMX271 and S108 meters weighied less than approximately 600 g. In bulk, as in weight, the HMX271, S108 and MiniGas were the most compact units of the monitors tested. The PhD and the G700 comprised a group of somewhat larger and bulkier models. Keep in mind that if a sampling pump is necessary, the bulk and weight of the pump must be added to all of the units except the G700 and the Compur Tritox M. The Compur units and the CGS units were clearly too large for workers who want a monitor that does not hinder movement or otherwise interfere with the performance of their work.

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All of the monitors, possibly excepting the CGS-90, should provide a full 8-hour day on a single battery charge.

All ten of the models studied are fairly simple to operate and maintain, although the investigators favor the HMX271, PhD, MiniGas and S108. The Tritox monitors are too sophisticated for personal monitoring applications; they are probably more suited for use by the professional industrial hygienist or certifying marine chemist. The operator manuals for the G700, HMX271 and S108 were particularly clear and easy to use, whereas the CGS-80/CGS-90 manuals were particularly difficult.

If temperature extremes are an important consideration, multigas monitors that operate on alkaline dry cells are not the best choice because these units failed at -12° C, turning off the monitor power and disabling the instrument. Both the Compur Tritox D and M also failed at this temperature resulting in an on-screen display message that read "T. out of range", indicating that the operating temperature was out of the instrument range.

All the multigas monitors that operate on rechargeable NiCd or lead-acid batteries (for example, PhD, CGS-80, CGS-90, HMX271, S108, and MiniGas), produced good sample recognition at all the evaluated temperatures (except for the Compur Tritox D and M as stated above). Replicate measurements indicate acceptable precision of readings at all temperatures (Tables 21-24), though the variations in meter steady-state readings were observed to be higher during the monitoring of methane and hydrogen sulfide, than those observed for oxygen. The S108, PhD, MiniGas and HMX271 monitors that use NiCd or lead-acid rechargeable batteries gave higher steady-state readings for 30% LEL CH_4 at -12° C than at 10°, 24° and 40°C.

The alarm response times for oxygen deficiency at -12° C for the multigas monitors using alkaline dry cells (CGM929A, MiniGas, and HMX271) could not be determined as these instruments shut off. The Compur Tritox D and M alarm response times could also not be determined at -12° C as these instruments were out of range, and both the Polytector G700 monitors shut off. The rechargeable battery instruments all gave relatively higher response times at -12°C than at other temperatures. At 10°, room temperature and 40° C, the alarm response times for all the monitors ranged from about 5-24 seconds and did not vary considerably with temperature. For most monitors operating at 10°, room temperature and 40° C, the combustible gas alarm response times decreased with increasing temperature.

At 100% relative humidity, the steady-state readings for gas levels were generally lower than those obtained under less humid conditions. This trend was observed for oxygen (approximately 1-3% decrease in reading), and was greater for combustible gas (6-27% decrease), and was most pronounced for toxic gas (12-39%). Exceptions to this trend were:

- the S108 gas monitors showed little humidity effect for oxygen readings,

- the S108 gas monitors exhibited lower readings for toxic and combustible gases, though these decreases were of similar magnitude for toxics and combustibles,

- the CGS 80-and 90 monitors gave out-of-range readings,

The alarm response times for all the monitors at 100% relative humidity were found to be higher by 3-43% during the monitoring of oxygen deficiency and 10-47% for oxygen overabundance. Similarly, results for other gases were higher by 3-68% for combustible gas and 11-300% for toxic gas.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to perform a comprehensive evaluation of ten personal multigas monitors selected by the U.S. Coast Guard Research and Development Center. The monitors were analyzed in terms of detection capability, operational parameters, physical characteristics, and other value-added-features. Further, this evaluation methodology was designed to be sufficiently comprehensive to allow new instruments to be evaluated and compared to the original ten.

The evaluation methods were selected based on instrument performance objectives for different conditions specified by the U.S. Coast Guard. In some cases, several methods were available to evaluate a particular criterion, and we chose the method that was most reproducible and most applicable to a field scenario. Similarly, we evaluated test data to determine which differences in measured parameters were relevant for field situations.

Two modes of use predominate– the monitors may be used to satisfy safety requirements prior to entry into an enclosed or confined space or, alternately, for personnel monitoring during work activities in potentially dangerous environments, whether in confined or open areas. Any recommendations on the relative quality of these monitors must be made in consideration of the different uses.

For routine personal monitoring during work functions portability, simplicity, economy and fail-safe reliability are important. On these grounds we believe that the HMX and MiniGas units rank at the top of the units tested, providing reliable warning capability without undue complexity or inconvenience. The S108 units were also among the better performing units in our lab study, but we have concerns that the relatively open design of the case could lead to damage by extraneous liquids or debris in a real-world work environment. Additionally the alarm points in the S108 were not conveniently set as with other units. The PhD and G700 units can be expected to perform as well as the above units, but their added bulk and weight placed them in the second rank as personal monitors, although these units also have data logging capability which may be useful for some situations. All five of these units can be belt mounted. We generally disagree with the use of monitors mounted by neck straps, regardless of whether the straps have quick release features.

For pre-entry screening remote sampling capability is more important while weight, size and unattended operation are less important. While other units can be purchased with an optional sample pump, only the G700 among the models tested had an effective sampling pump for remote sampling. Furthermore the G700 is the only one of the tested units well suited to "double duty"; it ranked very near the top tier for personal monitors yet unlike the other personal monitors, it included remote sampling capability and data logging capability. The slight extra weight of the G700 pays off well in added capability compared with the smaller, lighter units.

Table 33 summarizes the overall findings of this evaluation for the criteria in the table. This summary is not intended to place the ten instruments into an order of quality; but is intended to allow a user to decide which criteria are important for a particular situation and quickly determine how an instrument performed in that test.

Table 33. **Summary of results for the instruments evaluated in this study.**

MODEL	LINEAR RESPONSE TO CH4,O2, H2S	REMOTE SAMPLING	ACCURACY: CH4	ACCURACY: H2S	ACCURACY:O2	ALARM TIME	PORTABILITY	BULK	8HR BATT. CHG.	EASE OF USE	TEMP.EFFECTS @ -12C	TEMP.EFFECTS @ 10, 24, 40C	O2 ACCURACY @ 100%RH	CH4 ACCURACY @ 100%RH	H2S ACCURACY @ 100%RH	SCORE (a)	NOTES
PhD	+	+	+	+	+	++	++	+	+	++	+	+	+	+	+	18	b,f
CGM929A	+	+	+	+	+	+	+	++	+	+	-	+	+	+	+	14	e
CGS-80	+	+	-	--	+	+	+	-	+	+	+	+	+	-	-	4	d,f
CGS-90	+	+	-	--	+	+	+	-	-	+	+	+	+	-	-	2	d,f
G700B	+	+++	+	+	+	+	++	+	+	+	-	+	+	+	+	16	e
G700	+	+++	+	+	+	+	++	+	+	+	-	+	+	+	+	16	e
HMX271 (NiCd)	+	+	+	+	+	+++	++	++	+	++	+	+	+	+	+	19	b,c,f
HMX271 (Dry Cell)	+	+	+	+	+	+++	++	++	+	++	+	+	+	+	+	19	b,c,e
Compur Tritox D	+	+	-	--	+	+	+	-	+	-	-	+	+	+	+	4	f
Compur Tritox M	+	-	-	--	+	+	+	-	+	-	-	+	+	+	+	2	f
MiniGas (NiCd)	+	+	+	+	+	++	++	++	+	++	+	+	+	+	+	19	b,f
MiniGas (Dry Cell)	+	+	+	+	+	++	++	++	+	++	+	+	+	+	+	19	b,e
Scott S108	+	+	+	+	+	++	+++	++	+	++	+	+	++	+	++	22	b,c,f

a = score is calculated by adding 1 point for each "+" and subtracting 1 point for each "-"

b = instrument is belt mountable

c = user manual easy to read

d = user manual difficult to read

e = operates on dry-cell battery

f = operates on NiCd or lead-acid rechargeable battery

This table does not take into consideration the instrument costs (nearly the same) nor the ruggedness/survivability (impact resistance). See pp 114-115, and 135-136, resp.

ACKNOWLEDGEMENTS

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APPENDIX A

Reprint of the Paper Entitled

"Portable, Multigas Monitors For Air Quality Evaluation,

Part I: Principles of Detection"

By

Rene V. Arenas, Kenneth R. Carney,

and Edward B. Overton,

PORTABLE, MULTI-GAS MONITORS FOR AIR QUALITY EVALUATION
PART I - PRINCIPLES OF DETECTION

Rene V. Arenas, Kenneth R. Carney and Edward B. Overton[*]

ABSTRACT

The principles of detection for the different sensors installed in portable, direct-reading, multi-gas monitors for air quality evaluation in the workplace (especially in remote or confined spaces) are discussed, as well as the advantages and limitations for the various sensor types. The monitors considered are designed to be carried by the personnel to the worksite to provide a continuous spot analysis of the levels of oxygen, toxic gas, and combustible gas in the ambient air, and will trigger an alarm during conditions of oxygen deficiency or abundance, and the presence of dangerous concentrations of toxic or flammable gases.

INTRODUCTION

Monitoring of ambient air quality in the workplace is important not only for complying to the forever decreasing legislated permissible levels for various gases (1, 2), but also because of the potential health hazards toxic or flammable gases, and deficient or abundant oxygen levels may impose. One of the most convenient and "cost-effective" method of protecting people from exposure to these gases is for them to carry direct-reading, portable gas monitors to the worksite.

Portable gas monitors designed for the continuous monitoring of ambient air quality in the workplace is nothing new (3). The technology involved for the different sensors employed for gas detection is well documented (4-11). Majority of these older models, however, are designed for the continuous monitoring of only one or two gas levels (4, 5, 7). At present, there exist a multitude of new generation portable monitors that can continuously and simultaneously detect the spot concentrations of at least three gases (oxygen, toxic gas, and combustible gases) in the atmosphere. These latest versions are microprocessor-controlled and equipped with softwares allowing for the following: digital display of each gas level; data logging capability (that can be downloaded to a computer for data storage and further analysis); TWA (Time-Weighted Average), STEL (Short Term Exposure Limit) and peak value read-outs; automatic instrument self-diagnostic test; meter fault detection and alarms, low battery power condition, etc. (12). Unfortunately, the reliability of the monitor as an early warning device is still sensor-limited (3).

Under normal use the monitor operates in the diffusion mode although remote air sampling, which is important for determining ambient air quality in remote or confined areas prior to entry, using either a built-in or external pump, is possible. All are battery-powered devices equipped with alarms which will warn the worker of any immediately hazardous condition. Hence, these monitors will be useful for people working inside mine tunnels and shafts, oil refineries, chemical and pharmaceutical plants, steel mills, garages, storage tanks, silos, sewers, pipelines, and virtually any worksite, especially enclosed areas.

The objective of this review/tutorial paper is to provide the principles of detection for the sensors utilized in portable, multi-gas monitors. From the personal experience of the authors, such

information is at present not readily available, and most users are not aware of the mode of detection utilized for these devices. It is hoped that understanding these basic principles will enable the users and prospective buyers to identify the advantages and limitations of these instruments. Such knowledge may prove important when the monitors are used in different life-threatening situations. It is emphasized, however, that the discussion that follows is limited to portable, multi-gas instruments equipped with small, plug-in sensors designed to continuously and simultaneously monitor oxygen (O_2), either of the toxic gases carbon monoxide (CO) or hydrogen sulfide (H_2S), and combustible gas levels in the workplace. Hence, use of the term toxic gas in the text refers to either carbon monoxide or hydrogen sulfide, unless indicated otherwise. All the information given are very general in nature, and by intent, the discussion is not specific for any particular gas meter, unless stated otherwise. A summary of other detection modes employed in direct-reading instruments for the analysis of airborne gases and vapors are described elsewhere (6).

OPERATING PRINCIPLES OF THE DIFFERENT GAS SENSORS

A. Oxygen Sensor:

The oxygen sensor acts as both oxygen deficiency and oxygen abundance detector. Hence, the meter will warn the personnel whether the level of oxygen in the workplace is either sufficient for normal breathing, or is at a very high concentration which is potentially dangerous in the presence of combustible gases. Oxygen deficiency results primarily from the oxidation of metals, bacterial action, or displacement by other gases (13), while accumulation of oxygen results from leakages from various oxygen sources (e.g., oxygen cylinders). The average concentration of oxygen in breathing air is ca. 21% by volume (v/v), while the 1991 OSHA (Occupational Safety and Health Administration) definition of an oxygen deficient and oxygen enriched atmosphere is one wherein the concentration of oxygen is below 19.5 and at least 23% v/v, respectively (14).

Detector read-out is in % v/v oxygen. The normal operating range for the sensor is within 0 to 30%, while the normal factory-set alarm points for oxygen deficiency and abundance are within the range of 18 to 19.5, and 22 to 25% v/v, respectively.

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Electrochemical Cell

The universal sensor employed for oxygen detection in portable monitors is the electrochemical cell. Two modes of operation are available, namely: (a) galvanic or fuel cells; and (b) polarographic cells. There exist no fundamental difference in principle between these two modes, except that no external power is required for the fuel cell to operate, while an optimum voltage for the cathode is required to efficiently operate the polarographic cell (8).

Electrochemical cells employed as oxygen sensor are similar in construction to a metal/air battery (Figure 1). The cell is enclosed in a leak-proof container with a polymer membrane that selectively permits oxygen to diffuse into the electrolyte. For this particular system, the electrode reactions involved are as follows:

Cathode: $\qquad O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$ $\qquad$ (1)

Anode: $\qquad M + 2OH^- \longrightarrow MO + H_2O + 2e^-$ $\qquad$ (2)
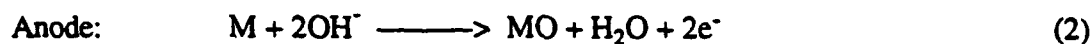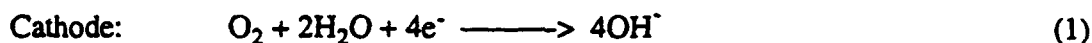
where M is a metal. Lead and gold are the common metals employed as anode and cathode for fuel cells, respectively. Based on reaction 2, the anode is consumed during the detection. Hence, the amount of metal (or anode) left in the cell determines the life of the sensor. The thermistor in Figure 1 consist of a metal oxide resistor and compensates for temperature effects on the detector response.

The most important feature of the oxygen sensor shown in Figure 1 is that the quantity of current produced by the net reaction is proportional to the partial pressure of oxygen in the air. The last feature is characteristic of sensors which utilize only a membrane as diffusion barrier. An alternative design is a set-up wherein oxygen is allowed to diffuse through a capillary fitted above the membrane. This innovation offers the following advantages: (a) temperature compensation for the cell output is not that significant since the rate of diffusion through a capillary is much less temperature-dependent than through a membrane; and (b) the quantity of current produced is proportional to the concentration of oxygen in the air (8).

The major advantage of using an electrochemical cell as oxygen sensor is that the detector response is specific, and approximately linear from 0 to 30% v/v oxygen. These sensors, however, require everyday calibration in clean, ambient air, and should not be used in atmospheres with highly oxidizing gases like chlorine and ozone (15). Sensor performance is also affected in atmospheres with 100% relative humidity (RH) due to the condensation of water on the diffusion barrier. Finally, applicability of the sensor is limited during freezing conditions since the cell contains an aqueous electrolyte (16). For some insight into manufacturer specifications, the C/Y CiTiceL, used as oxygen electrochemical sensor in many personal monitors, has a minimum and maximum operating range of 0 to 2 and 0 to 30% v/v oxygen, respectively; a response time of less than 20 seconds to 95% of concentration; an operating life of 12 months in air; a storage life of 6 months; and can be used continuously in conditions of -15 to +40° C and 0-99% relative humidity (15). The S108 oxygen electrochemical cell (17), on the other hand, has an operating range of 0.0 to 25.0%, an accuracy of ± 0.8% at ambient temperatures, a response time of 20 seconds to 63% of oxygen change, and temperature limits of -3 to 60 and 0 to 40° C for storage and operation, respectively.

B. Toxic Gas Sensor:

Unlike the immediate hazards imposed by atmospheres with insufficient oxygen supply or flammable/explosive levels of combustible gases, monitoring toxic gas concentration in the workplace is important both for the acute and chronic effects of these gases to human health. This is why different standards are recommended by both OSHA and ACGIH (American Conference of Governmental Industrial Hygienists) regarding exposure to toxic gases. Values for carbon monoxide, hydrogen sulfide, and some hydrocarbons are listed in Table 1. Further details about these recommended limits can be obtained elsewhere (18, 19). The common sources of carbon monoxide and hydrogen sulfide are incomplete combustion and decomposition of biodegradable materials, respectively (16). Hydrogen sulfide can also occur as a by-product in refineries, some plastic and rubber processes, and tanneries (1).

The two most popular sensors employed for toxic gas monitoring in the workplace include: (a) electrochemical cells; and (b) MOS (metal oxide semiconductor) sensors. Detector read-out is in ppm of toxic gas. The normal sensor operating range is from 0 to 500, up to 2000 ppm, while the alarm point is normally set to a minimum of 10 ppm of toxic gas. Due to the chronic effects of prolonged exposures to toxic gases, state-of-the-art monitors are equipped with alarms that will warn the worker if TLV (Threshold Limit Value), TWA, STEL and ceiling limits have been exceeded (12).

1. Electrochemical Cell

A typical carbon monoxide/hydrogen sulfide electrochemical cell consist of three electrodes: sensing (anode), counter (cathode), and reference electrodes, separated by a thin layer of electrolyte (Figure 2). As with the oxygen electrochemical cell, sample introduction can be carried out by diffusion through a membrane or capillary diffusion barrier, with the sensor response being proportional to the concentration of toxic gas in the latter case. The toxic gas is oxidized at the surface of the sensing electrode (reactions 3 and 4), while oxygen in air is reduced to water at the counter electrode (reaction 5). Sensor specificity for either carbon monoxide or hydrogen sulfide

Sensing Electrode: $$CO + H_2O \longrightarrow CO_2 + 2H^+ + 2e^- \tag{3}$$

$$H_2S + 4H_2O \longrightarrow H_2SO_4 + 8H^+ + 8e^- \tag{4}$$

Counter Electrode: $$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O \tag{5}$$
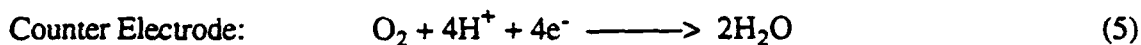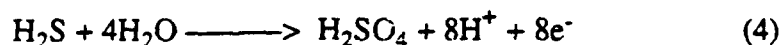
can be achieved by: (a) choosing the appropriate sensing electrode material designed to catalyze the oxidation of the toxic gas; (b) controlling the voltage of the sensing electrode; and (c) through the use of in-board filters which can remove acid gases (SO_2, NO, NO_2), trace environmental gases, and trace organic materials (15).

The major advantage of using electrochemical cells for toxic gas monitoring is that the detector output is highly specific and linear from 0 to 50 ppm (21) for carbon monoxide or hydrogen

sulfide. Similar to the oxygen sensor, performance of the toxic gas electrochemical cell is relatively unaffected by relative humidity except at 100% RH, and freezing conditions should be avoided. For an example of manufacturer specifications, the MiniGas toxic gas sensor has an operating range of either 0 to 999 ppm CO or 0 to 499 ppm H_2S. The accuracy for the CO reading is $\pm$ 5 ppm at 100 ppm, while similar values for H_2S are $\pm$ 2 ppm at 50 ppm. The rise time to 90% of concentration is 30 ± 15 seconds and 90 ± 30 seconds for CO and H_2S, respectively (22).

As a final note, cells specific for the following toxic gases are also available: SO_2, NO, NO_2, H_2, Cl_2, and HCN. The reactions at the sensing electrode for these gases are given in reactions 6 to 11 (15). In situations where the identity of possible toxic gases are known, availability of these

Sensing Electrode:

$$SO_2 + 2H_2O \longrightarrow H_2SO_4 + 2H^+ + 2e^- \qquad (6)$$

$$NO + 2H_2O \longrightarrow HNO_3 + 3H^+ + 3e^- \qquad (7)$$

$$NO_2 + 2H^+ + 2e^- \longrightarrow NO + H_2O \qquad (8)$$

$$H_2 \longrightarrow 2H^+ + 2e^- \qquad (9)$$

$$Cl_2 + 2H^+ + 2e^- \longrightarrow 2HCl \qquad (10)$$

$$2HCN + 2H_2O \longrightarrow 2HCOH + 2H^+ + N_2 + 2e^- \qquad (11)$$
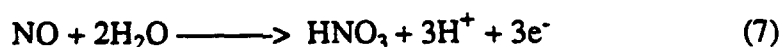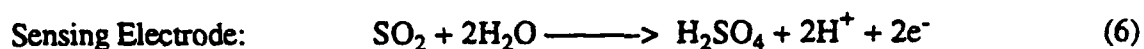
highly-specific toxic gas sensors would be a definite advantage when using monitors that allow the worker to simply plug in the appropriate toxic gas sensor (e.g., as in the TMX410 (23) wherein any two of the following toxic gas sensors (CO, H_2S, SO_2, NO_2, and Cl_2) can be installed together with the oxygen and combustible gas sensors).

2. MOS Sensor

Figure 3 shows a typical MOS sensor used for the detection of toxic and combustible (*vide infra*) gases. The sensing element consist of a heated metal oxide semiconductor chosen from n-type or p-type oxides of transition and heavy metals (e.g., tin, zinc or nickel). Upon adsorption of the gas molecules onto the heated surface, oxidation/reduction reactions occur resulting in the trapping or release of charge carriers at the surface, and subsequently a proportional change in the

electrical conductivity of the metal oxide. This change in conductivity is related to the concentration of the gas of interest in the sample air. Sensor selectivity is achieved by varying either the composition or surface temperature of the MOS (7, 9-11, 16, 21).

Advantages of using MOS sensors include the ability to detect low concentrations of toxic gases ranging from 0 to 100 ppm (7), and a wide temperature applicability since the MOS surface is heated to above 100° C. The output is, however, nonlinear and nonspecific (16). Hence, MOS sensors will respond to a wide range of toxic gases, and are calibrated to provide a quantitative read-out for a particular toxic gas. According to the proponents of this technology (16, 21), this nonspecificity can actually be an advantage in situations wherein unknown toxic gases may be present in the atmosphere. For an insight into manufacturer specifications, the Tritector Model CGS-90 has an average sensor life of 2 to 3 years, and a response time of less than 60 seconds (24).

C. Combustible Gas Sensor:

Monitoring the concentration of combustible gases in the workplace is the most effective way of reducing the risk of fires and explosions. Accumulation of combustible gases usually results from leakages from gas pipes and cylinders, and other combustible gas storage facilities.

Two types of sensors are used for detection of combustible gases, namely: (a) catalytic combustion/thermal conductivity sensors; and (b) MOS sensors. Detector read-out is in % LEL (Lower Explosive Limit) of combustible gas. By definition, the lower explosive limit is the concentration of combustible gas in air below which they cannot be ignited. The LEL values in % v/v for common combustible gases, including those for the toxic gases, are shown in Table 1. The normal operating range for the sensor is within 0 to 100% LEL, while the normal factory-set alarm point is at 10% LEL, although some models have alarm settings ranging from 20 to 40% LEL. Most instruments are calibrated for methane, although occasionally propane and pentane are used.

1. Catalytic Combustion/Thermal Conductivity Sensor

Detection using the catalytic combustion sensor (Figure 4A) is achieved by quantitatively measuring the amount of heat evolved when the combustible gas is catalytically burned to carbon

dioxide and water. It is emphasized that although the combustible gas which diffuses into the sensor is ignited, there exist no danger of propagating the flame outside the sensor since the sintered metal disc also acts as a flame trap or flame arrestor. The sensor operates in the balanced Wheatstone electrical bridge circuit in which two opposing arms are made of platinum filaments. One of the filaments (active catalyst in Figure 4A) is heated above the ignition temperature of the gas to be measured, and is exposed to the air. Any combustible gas oxidized by the heated filament will result in a change in the electrical resistance of that filament which is proportional to the combustible gas concentration. The second filament (passive catalyst in Figure 4A), on the other hand, compensates for variations in ambient temperature and humidity (7).

The platinum wire employed acts as both temperature sensor and electrical heater. In earlier models, platinum was also used as catalyst for the combustion process. Platinum, however, is relatively a poor catalyst for combustion, especially for the continuous monitoring of methane wherein temperatures greater than 800° C (at which platinum evaporates) are required. More recent combustible gas sensors utilize oxides of palladium which are more active catalyst than platinum, requiring temperatures ranging from 500 to 600° C for the oxidation of methane (11, 21). These more recent models are commonly called "catalytically-treated beads", wherein a coiled platinum wire is embedded in a porous ceramic bead impregnated with the catalyst.

A limitation of the catalytic combustion sensor is that a nonlinear response is obtained at high concentrations of combustible gas, or when incomplete oxidation of the flammable gas occurs due to insufficient oxygen supply. In earlier combustion sensor models, deviation from linearity begins to occur at ca. 75 to 80% LEL (11, 21). State-of-the-art catalytic combustion sensors, however, exhibit a linear response up to at least 100% LEL.

The nonlinear response characteristic of combustion sensor types has been solved through the use of thermal conductivity sensors (Figure 4B), wherein a linear response is obtained over the entire range of combustible gas concentration. The thermal conductivity sensor consists of a slightly heated catalytic element (T_1 in Figure 4B) which is exposed to the sample air, and an isolated compensating element (T_2 in Figure 4B) which is in contact only with the reference gas.

In the presence of the combustible gas, a temperature difference is established resulting in a proportional change in the resistance of the thermal conductivity bridge circuit. However, since most portable monitors have alarm points at low % LEL (normally at 10% LEL), the ability to measure combustible gas concentrations from 0 to 100% LEL is not that essential. The latter trend, and the simplicity of detection largely accounts for the continued use and popularity of catalytic combustion sensors, which have been used for over half a century (16, 21). Further information about thermal conductivity sensors can be obtained from reference (11).

The relatively low % LEL alarm settings recommended for portable monitors is intended not just for added safety, but also to take into account the limitations of the catalytic combustion sensor. The sensor will respond to any gas or vapor which will burn in the presence of atmospheric oxygen. Hence, the detection is generally non-specific, although some selectivity can be achieved by selection of the filament temperature. For quantitative measurements, it should be noted that the displayed reading will only be true for the combustible gas used for calibrating the sensor. Thus, a meter calibrated using methane can only approximate the presence or absence of other combustible gases. To compensate for this lack of specificity, LEL correction factors (Table 2) have been established (11, 26). Its effective use, however, require knowing what combustible gas is present, and is inapplicable if more than one combustible gas is encountered. Other limitations are that the combustion sensor can "burn out" in atmospheres with very high concentrations of combustible gases, and the sensor cannot detect combustible gas levels in the absence of oxygen. The minimum required concentration of oxygen is about 16% v/v (21). The catalyst employed is also subject to "poisoning" by compounds containing either silicon, lead, phosphorus or halogens. "Poisoning" refers to the decrease in catalyst activity due to surface coverage of active sites arising from the deposition of solid decomposition products from the latter compounds (11). Hence, it is essential to know in advance whether the catalytic combustion sensor installed in the monitor is poison-resistant or not. Finally, catalytic combustion sensors lack sensitivity, and are normally used to detect combustible gas levels ranging from 1,000 to 50,000 ppm (21).

For some insight into manufacturer specifications, the Polytector G 700/3 combustible gas sensor has a response time of less than 10 seconds to 90% of concentration, a lifespan greater than 12 months, and can be used continuously in temperatures ranging from -20 to +40° C. The combustion sensor employed is also poison-resistant, and exhibits a linear response up to ca. 12 to 13% methane. The operating range for the catalytic combustion sensor and the thermal conductivity sensor is between 0 to 100% LEL or 0 to ca. 5% v/v, and 0 to 99.9% v/v of methane, respectively (25, 27).

2. MOS Sensor

The principle of detection involved for combustible gas MOS sensors is similar to that discussed earlier for toxic gas MOS sensors. This sensor type can detect very low concentrations of combustible gases ranging from 0 to 10 ppm, up to about 200% LEL (7). Other advantages of MOS over conventional catalytic combustion sensors include better sensitivity (by ca. two orders of magnitude); greater stability (since the sensor will not burn out in atmospheres with high combustible gas concentrations, and is not subject to "poisoning"); less current and voltage requirement for operation (due to the lower heating temperatures used ranging from 200 tc 350° C); and finally, the MOS sensor can detect combustible gas levels even in places without oxygen (7, 10, 21).

The major drawback in its use as a universal combustible gas sensor is its lack of specificity. Any gas which can be adsorbed by the metal oxide will probably result in changing the conductivity of the sensor. Thus, similar to catalytic combustion sensors, the combustible gas MOS sensor is also calibrated to respond to a particular combustible gas.

CONCLUSIONS

The risk involved when working in areas wherein oxygen deficiency or abundance, and the presence of dangerous levels of toxic and combustible gases can occur can be significantly reduced through the use of portable, multi-gas monitors. These i   ents are direct-reading devices which can provide a continuous spot analysis of the ever-changing air quality in the workplace.

Multi-gas capability is achieved through the installation of several gas sensors in the monitor. Hence, the analytical capability of the instrument is determined solely by the particular sensor type employed. However, the sensors at best can only provide approximate concentrations of the various gases for which it was calibrated for, and is incapable of absolutely identifying and quantifying the presence of these air contaminants. Therefore, when the alarm is triggered suggesting the existence of potentially hazardous conditions, site evacuation and other precautionary measures should be immediately performed. Finally, for maximum benefit, it is desirable to know in advance what toxic and flammable gases are most likely to be encountered in the workplace.

ACKNOWLEDGMENTS

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TABLE 1. Recommended limits and LEL values for selected air contaminants.

Air Contaminant	OSHA Final Rule Limits [a]			ACGIH [b]		LEL [c] (% v/v)
	TWA (ppm)	STEL (ppm)	Ceiling (ppm)	TLV-TWA (ppm)	TLV-STEL (ppm)	
Carbon Monoxide	35	—	200	50	400	12.5
Hydrogen Sulfide	10	15	—[d]	10	15	4
Methane	—	—	—	—	—	5.3
Ethane	—	—	—	—	—	3.0
Propane	1000	—	—	—	—	2.3
Butane	800	—	—	800	—	1.9
Pentane	600	750	—	600	750	1.5
Gasoline	300	500	—	300	500	1.3

[a] Limits given are in parts of vapor or gas per million parts of contaminated air by volume at 25° C and 760 torr. TWA, STEL, and ceiling values were obtained from reference (18).

[b] TLV-TWA and TLV-STEL values were obtained from reference (19).

[c] LEL values were obtained from reference (20).

[d] Acceptable ceiling concentration for H_2S is 20 ppm. The acceptable maximum peak above the acceptable ceiling concentration for an 8-hr shift is 50 ppm for a maximum duration of 10 minutes once only if no other measurable exposure occurs (18).

TABLE 2. LEL correction factors (or multipliers) for the catalytic combustion sensor (26). [a, b, c]

Gas Being Sampled	Calibration Gas							
	Acetone	Acetylene	Butane	Hexane	Hydrogen	Methane	Pentane	Propane
Acetone	1.0	1.2	1.1	0.7	1.8	1.4	0.9	1.1
Acetylene	0.8	1.0	0.9	0.6	1.5	1.1	0.7	1.0
Benzene	1.1	1.3	1.2	0.8	1.9	1.4	0.9	1.2
Butane	0.9	1.1	1.0	0.6	1.6	1.2	0.8	1.1
Ethane	0.8	0.9	0.8	0.5	1.4	1.0	0.7	0.9
Ethanol	0.9	1.1	1.0	0.7	1.7	1.3	0.8	1.1
Ethylene	0.7	0.9	0.8	0.5	1.3	1.0	0.6	0.8
Hexane	1.4	1.7	1.5	1.0	2.5	1.9	1.3	1.6
Hydrogen	0.6	0.7	0.6	0.4	1.0	0.8	0.5	0.7
Isopropanol	1.2	1.5	1.3	0.9	2.1	1.6	1.1	1.4
Methane	0.7	0.9	0.8	0.5	1.3	1.0	0.7	0.8
Methanol	0.7	0.8	0.7	0.5	1.2	0.9	0.6	0.8
Pentane	1.1	1.4	1.2	0.8	2.0	1.5	1.0	1.3
Propane	0.9	1.1	0.9	0.6	1.5	1.2	0.8	1.0
Styrene	1.7	2.1	1.9	1.2	3.0	2.3	1.5	2.0
Toluene	1.1	1.4	1.2	0.8	2.0	1.5	1.0	1.3
Xylene	1.4	1.7	1.5	1.0	2.5	1.9	1.3	1.6

[a] For an example of how to use these table, to determine % LEL pentane using a catalytic combustion sensor calibrated for methane, simply multiply the monitor reading by 1.5. Hence, for a reading of 20% LEL, the approximate % LEL pentane is 30% LEL (i.e., 20*1.5).

[b] Multiplier accuracy is ±25%.

[c] Methane is the recommended calibration gas when using the sensor in atmospheres suspected to be contaminated with silicone, sulfur, lead or halogen-containing compounds.

FIGURE CAPTIONS

Figure 1. Oxygen electrochemical sensor (7, 8).

Figure 2. Toxic gas electrochemical sensor [Courtesy of City Technology Ltd. (15)].

Figure 3. Toxic gas MOS sensor [Courtesy of Enmet Corporation (16)].

Figure 4. Combustible gas (A) catalytic combustion, and (B) thermal conductivity sensors [Courtesy of GfG Gas Electronics, Inc. (25)].

O₂   O₂   – – – Membrane

Cathode

Electrolyte (e.g., KOH)

Anode

Thermistor

Capillary Diffusion Barrier

O-Ring Seal

Sensing Electrode

Reference Electrode

Counter Electrode
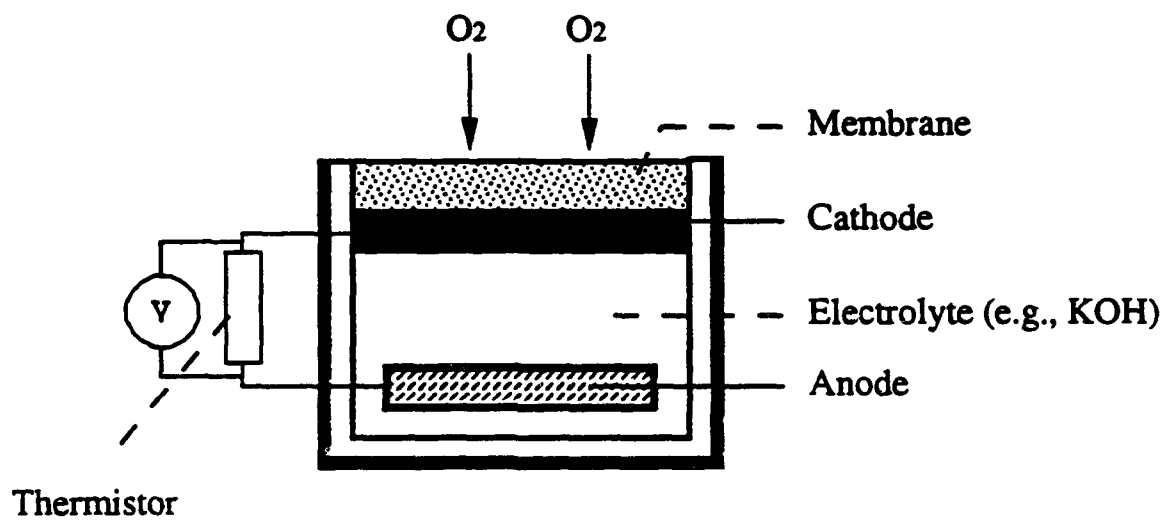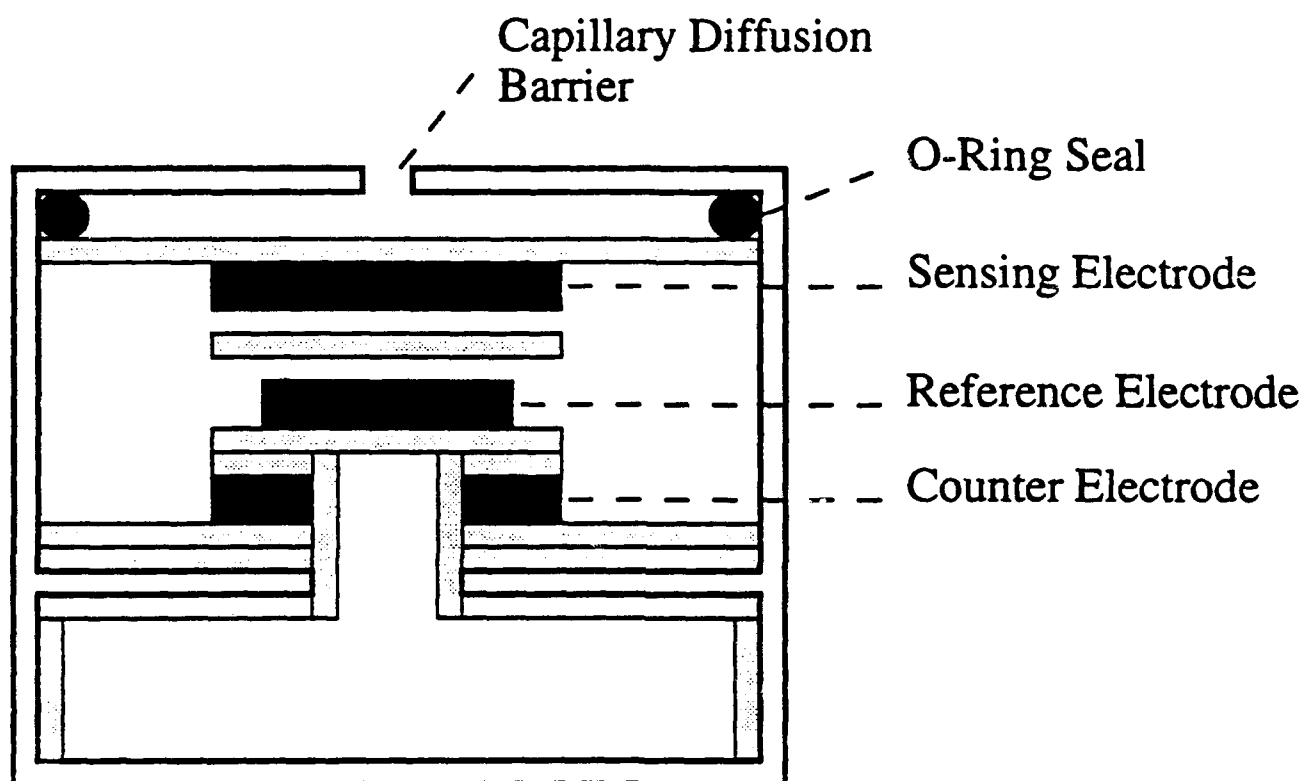
Sintered
Stainless
Steel
Cup

Sensor

Heater
Coil

Noble
Metal
Wire

Nickel
Pins

(A)

Sintered Metal

Passive Catalyst

Sensor Cell

Flammable Gas

Active Catalyst

(B)

Sensor Cell

T_1

Comparison Cell

Flammable Gas

Platinum Wire

Sensor Housing

T_2
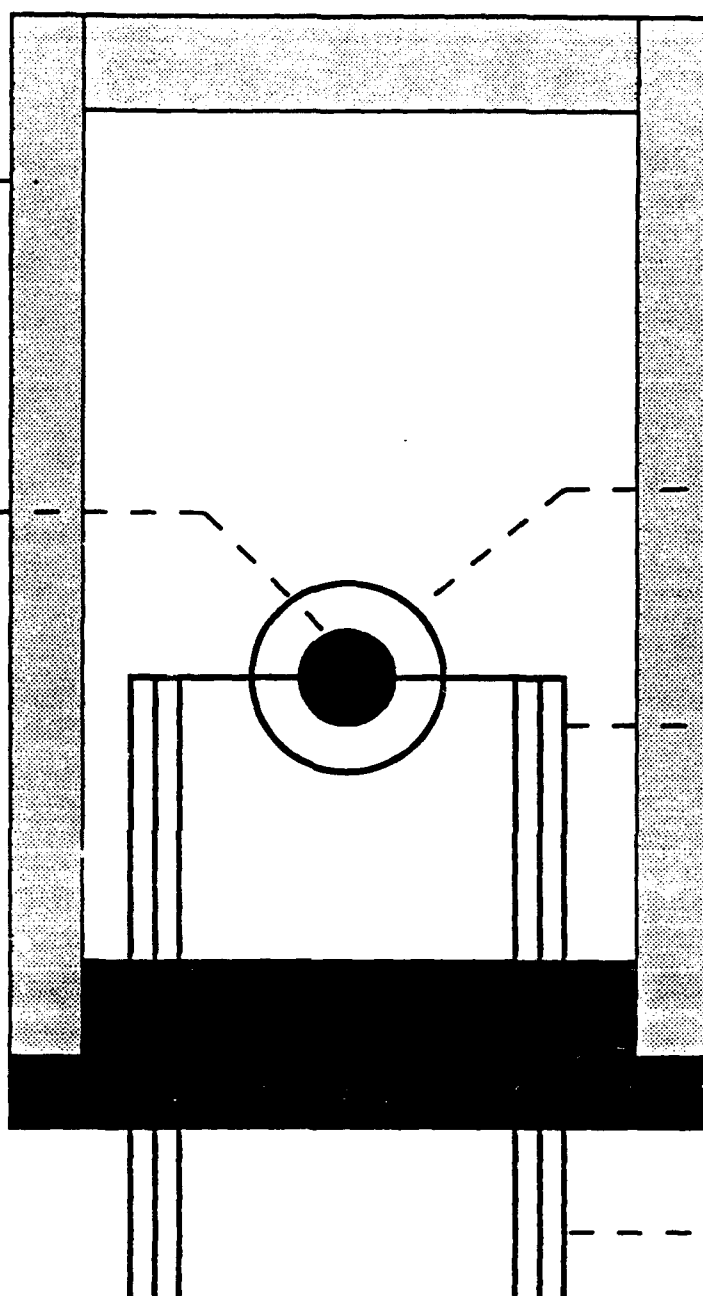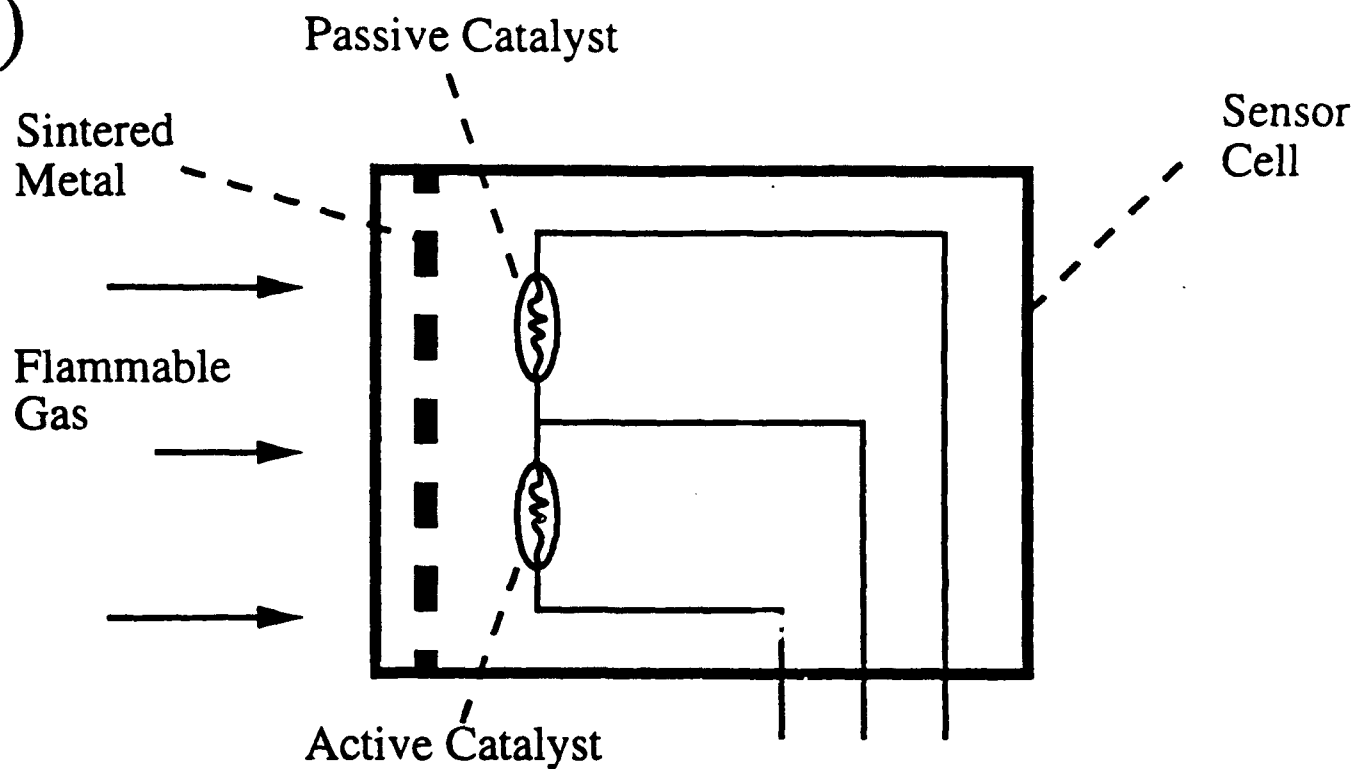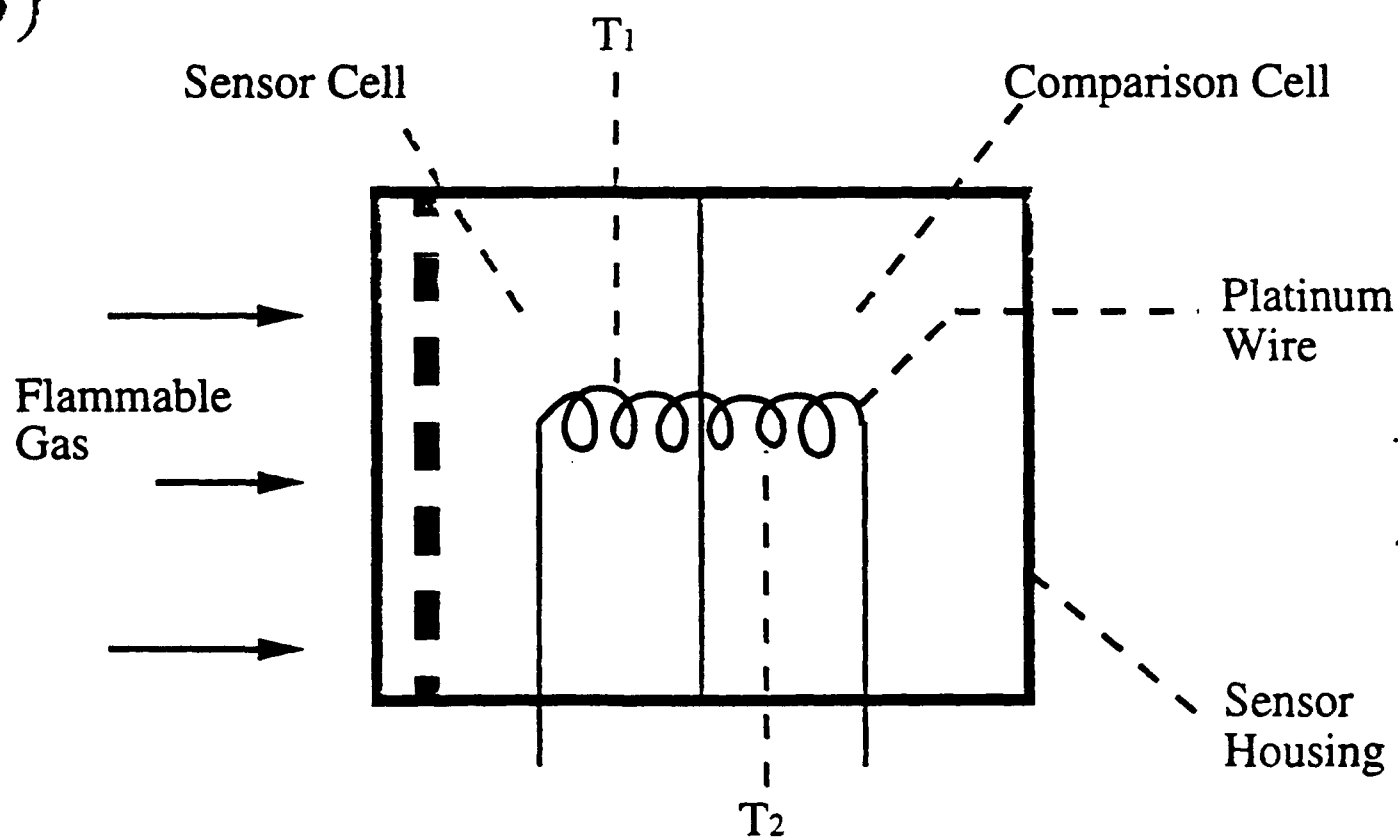
APPENDIX B

Reprint of the Paper Entitled

"Portable, Multigas Monitors For Air Quality
Evaluation,

Part II: Survey Of Current Models"

By

Rene V. Arenas, Kenneth R. Carney,

and Edward B. Overton,

American Laboratory, Submitted.

PORTABLE, MULTIGAS MONITORS FOR AIR QUALITY EVALUATION

PART II - SURVEY OF CURRENT MODELS

Rene V. Arenas, Kenneth R. Carney,

and Edward B. Overton*

ABSTRACT

At present there exist a multitude of new generation, portable multigas monitors designed to continuously and simultaneously detect the spot concentrations of oxygen, toxic gas, and combustible gas in confined spaces. The paper identifies the desirable features of an ideal multisensor gas monitor, and enumerates the different models currently available.

INTRODUCTION

At present there exist a multitude of new generation, portable monitors that can continuously and simultaneously measure the spot concentrations of three gas types (oxygen, toxic gas, and combustible gas) in the workplace. These direct-reading instruments are particularly useful for personnel working in confined spaces (e.g., manholes, silos, ship compartments, storage tanks, pipelines, etc.), allowing them to monitor the air quality in the enclosed area prior to entry and for the duration of the work. Its use has become a necessity not only for protecting workers from exposure to the dangers of oxygen deficiency/abundance or the presence of toxic and flammable gases, but also for complying with the new confined space law (29 CFR 1910.146 - "Permit Required Confined Spaces") issued by OSHA (Occupational Safety and Health Administration) last February 1992.[1-4] According to a recent survey conducted by OSHA,[3] many deaths and injuries in confined spaces are caused by atmospheric hazards which have been classified into three categories, namely 1) toxic, 2) asphyxiating, and 3) flammable or explosive atmospheres. Hence, the new law requires testing of the confined space atmosphere for these gases. Utility of these devices, however, are not limited to enclosed areas but also applies wherever toxic or flammable gases may exist (i.e., for industrial hygiene and safety).

Multigas capability in these monitors is achieved through the use of specific sensors for each gas. The principles of detection for the various sensors utilized have recently been reviewed in Part I of the series.[5] The present paper lists the desirable features and the different models of portable, multisensor gas monitors currently available. Similar to Part I, the discussion is limited to monitors equipped with small, plug-in sensors designed to continuously and simultaneously detect the spot concentrations of at least the

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following gases: oxygen (O_2), either of the toxic gases carbon monoxide (CO) or hydrogen sulfide (H_2S) - which are the most common toxic gases encountered in confined spaces,[4] and combustible gases. It is hoped that knowing these features and the various models available will assist prospective users in deciding what model is suited for their particular application.

DESIRABLE FEATURES OF AN IDEAL MULTIGAS MONITOR

Listed in *Table 1* are the desirable features of an ideal multisensor gas monitor for confined space applications. The sequence used does not imply any order of importance for these different features. Except for the features discussed below, further details for the other desirable features enumerated in *Table 1* will be published elsewhere.[6]

The speed, selectivity, sensitivity, accuracy, and reproducibility of the monitor response for a given gas is dependent on the particular sensor type employed. These parameters have already been discussed, and typical values for the different types of sensors utilized can be obtained from Part I of the series.[5] It is emphasized, however, that monitor response for a given gas can only be as good as the sensor employed. Hence, it is important to know what types of sensors are installed to determine the capabilities and limitations of the device.

The installation of microprocessor circuitry and softwares (essentially) differentiates state-of-the-art portable gas monitors to their older counterparts.[7] It may be argued that the incorporation of microprocessor technology into the system has revolutionized these instruments resulting in simplicity of operation (e.g., automatic self-diagnostic check, automatic zeroing, and automatic calibration), data storage capability, and the ability to perform electronic calculations (e.g., averaging). The two latter features allow the monitor to carry out the following task: 1) to store and display peak values, 2) to function as a dosimeter through the calculation of time weighted averages (TWA), and 3) to detect when TWA, TLV (threshold limit value), STEL (short term exposure limit), and ceiling limits have been exceeded. Some monitors also function as data loggers, allowing the operator to download all the information collected and stored during a monitoring period to a computer for further analysis. Examples of these different information may include ambient temperature, instrument operating time, TWA exposure to toxic gases, peak or highest levels encountered, number of alarms, and sensor reading for each gas analyzed

per minute for the entire period that the instrument was used.

Finally, it should be noted that remote sampling capability is achieved through the use of either 1) a built-in or attachable (motorized or manual) sampling pump which can draw air samples from the confined or remote space, or 2) an extension cable with the appropriate sensors mounted in a housing fitted at the end, or an extension pole or rope where the monitor can be mounted or attached. Typical tube lengths vary, and can be 30 meters long.

CURRENT MODELS OF MULTIGAS MONITORS

The current models available for portable, multigas monitors are enumerated in *Table 2*. No guarantee is given that the list includes all models in the market today, since it is limited only to manufacturers who responded to the survey. It should be noted that all the specifications given were obtained solely from information supplied by the manufacturer or distributor.

Table 2 shows that there are at least sixteen manufacturers of these combination gas monitors. There would have been more companies in the list if monitors which can detect one or up to two gases simultaneously were included, but use of such a device may not completely satisfy the OSHA requirement.

At present, the maximum number of sensors that can be fitted simultaneously is five. Although the customer can normally choose what sensors or calibration he wants, for confined space monitoring these instruments will at least be supplied with sensors for oxygen, combustible gas (usually methane), and toxic gas (usually hydrogen sulfide or carbon monoxide). Hence, the user usually only has a choice of what toxic gas(es) to monitor. Although not indicated in *Table 2*, equally important is the ability of the monitor to function as a one sensor, two sensor or multisensor device.

The cost of each monitor ranges from ca. $1300 to 3000, depending on the sophistication desired, and the accessories included. Proper operation of the monitor, however, will require the purchase of the appropriate calibration gas(es), and compliance with OSHA's new guidelines for work in confined spaces may necessitate the purchase of an optional sampling pump, if not already incorporated in the system.

CONCLUSIONS

There are at least sixteen manufacturers providing different versions of portable, multisensor gas monitors today, making it very difficult for the prospective user to decide which model to select. For confined space application wherein the device is intended to be carried or worn by the worker at all times to continuously monitor the air quality in the working area, the basic factors to consider are reliability (i.e., sensor response, intrinsic safety, and ruggedness), portability, and ease of operation. The capability to function as a dosimeter is also essential since this allows the monitor to alert the worker whenever TWA, STEL or ceiling limits have been exceeded. Finally, although low cost is always preferred, in the long run the most cost-effective system to purchase is one that can be upgraded whenever necessary. Hence, these will be monitors which would allow the user to 1) choose and install the appropriate gas sensors required, 2) choose between a simple (or basic) and technically complicated operation modes, 3) install a sampling pump, and 4) incorporate data logging capability or additional softwares, upgrading a simple direct-reading combination gas monitor to a highly sophisticated hygiene instrument.

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Table 1. Desirable features of an ideal portable, multisensor gas monitor.

- Fast, specific, sensitive, accurate, and reproducible sensor response.
- Microprocessor-controlled.
- With data logging capability.
- Easy to operate, and requires minimum maintenance.
- With remote sampling or sensing capability.
- With both visible and audible alarms.
- With easy-to-read, self-illuminating digital display which will provide a simultaneous read-out for all gases being monitored.
- Rugged and durable.
- Certified to be intrinsically safe.
- Failsafe.
- Can be operated using either a rechargeable battery pack or disposable dry cells that are easily interchangeable.
- Compact and light.

Table 2. Survey of portable, multisensor gas monitors for air quality evaluation in confined spaces.

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously [a]	Gases Monitored [b]	Concentration Range [c]	Sensor Type [d]	Simultaneous Digital Display of All Gas Levels? [e]	With Built-in Sampling Pump? [f]	With Data Logging Capability? [g]	Dimensions, L x W x H (cm)	Weight [h] (kg)
Alm USA	Logic 3000	3	O_2	0.1-25%	Electrochemical	No	No	Yes	39.9-47.0 x 6.4 x 6.4	0.9-1.0
			Combustibles	0-100% LEL or 0-50,000 ppm	MOS					
			H_2S	0-500 ppm or 0-1000 ppm	Electrochemical					
			CO	0-1000 ppm	Electrochemical					
			SO_2	0-2000 ppm	Electrochemical					
				0-100 ppm or 0-500 ppm						
			Cl_2	0-250 ppm	Electrochemical					
			NO	0-1500 ppm	Electrochemical					
			NO_2	0-750 ppm	Electrochemical					
			I_2	0-2000 ppm	Electrochemical					
			HCN	0-100 ppm	Electrochemical					
			HCl	0-100 ppm	Electrochemical					
Bacharach	Sentinel 4	4	O_2	0-25%	Electrochemical	No	No	Yes	19.7 x 11.4 x 5.1	1.1
			Combustibles	0-100% LEL	Catalytic					
			H_2S	0-200 ppm	Electrochemical					
			CO	0-500 ppm	Electrochemical					
Biosystems	PHD	4	O_2	0-25%	Electrochemical	Yes	No	Yes	18.3 x 10.9 x 5.6	0.6
			Combustibles	0-100% LEL	Catalytic					
			H_2S	0-140 ppm or 0-675 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO_2	0-500 ppm	Electrochemical					
			Cl_2	0-7 ppm	Electrochemical					
			NO_2	0-7 ppm	Electrochemical					
			HCN	0-200 ppm	Electrochemical					
			NH_3	0-100 ppm	Electrochemical					
	Cannonball	4	O_2	0-25%	Electrochemical	Yes	Yes	Yes	23.5 x 16.5 x 15.2	2.7
			Combustibles	0-100% LEL	Catalytic					
			H_2S	0-140 or 675 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO_2	0-500 ppm	Electrochemical					
			NO_2	0-7 ppm	Electrochemical					
			HCN	0-200 ppm	Electrochemical					
			NH_3	0-100 ppm	Electrochemical					

Table 2. (Continued).

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously[a]	Gases Monitored[b]	Concentration Range[c]	Sensor Type[d]	Simultaneous Digital Display of All Gas Levels?[e]	With Built-in Sampling Pump?[f]	With Data Logging Capability?[g]	Dimensions, L x W x H (cm)	Weight[h] (kg)
Enmet[i]										
	CGS-20M	3	O2 Combustibles H2S CO	0-25% 0-10% LEL or 0-20% LEL 0-10 ppm 0-50 ppm	Electrochemical MOS MOS MOS	No (With a meter read-out)	No	No	14 x 9.5 x 5.7	1.1
	CGS-80	3	O2 Combustibles H2S CO	16-25% 0-25% LEL 0-25 ppm 0-125 ppm	Electrochemical MOS MOS MOS	No (Bar graphs for oxygen and combustible or toxic gases)	No	No	22.8 x 11.4 x 5.7	2.8
	CGS-90	3	O2 Combustibles H2S CO	0-99.9% 0-25% LEL 0-25 ppm 0-125 ppm	Electrochemical MOS MOS MOS	Yes (Bar graphs for combustible and toxic gases)	No	No	19.2 x 11.1 x 6.1	1.6
	CGS-100	3	O2 Combustibles H2S CO	0-99.9% 0-50% LEL 0-50 ppm 0-300 ppm	Electrochemical MOS MOS MOS	Yes (Bar graphs for combustible and toxic gases)	No	No	30 x 20 x 6	2.9
	QUAD-400	4	O2 Combustibles H2S CO	0-99.9% 0-60% LEL 0-30 ppm 0-100 ppm	Electrochemical Catalytic Electrochemical Electrochemical	Yes	No	Yes	19.7 x 14.0 x 6.6	1.8

Table 2. (Continued).

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously[a]	Gases Monitored[b]	Concentration Range[c]	Sensor Type[d]	Simultaneous Digital Display of All Gas Levels?[e]	With Built-In Sampling Pump?[f]	With Data Logging Capability?[g]	Dimensions, L x W x H (cm)	Weight[h] (kg)
Gas Tech	GX-82	3	O2 / Combustibles / H2S / CO / SO2	0-50% / 0-99% LEL / 0-99 ppm / 0-500 ppm / 0-99 ppm	Electrochemical / Catalytic / Electrochemical / Electrochemical / Electrochemical	Yes	No	No	18.4 x 8.6 x 5.1	1.1
	GX-86	4	O2 / Combustibles / H2S / CO / SO2	0-40% / 0-99% LEL / 0-99 ppm / 0-300 ppm / 0-50 ppm	Electrochemical / Catalytic / Electrochemical / Electrochemical / Electrochemical	Yes	No	No	18.4 x 12.7 x 6.4	1.4
	GX-91	4	O2 / Combustibles / H2S / CO / SO2	0-40% / 0-100% LEL / 0-100 ppm / 0-500 ppm / 0-50 ppm	Electrochemical / Catalytic / Electrochemical / Electrochemical / Electrochemical	Yes	No	Yes	16.5 x 15.6 x 7.0	1.7
	Safe T Mate Type 300	3	O2 / Combustibles / H2S	0-30% / 0-100% LEL / 0-500 ppm	Electrochemical / Catalytic / Electrochemical	Yes	No	No	12.7 x 7.1 x 4.1	0.6
	Safe T Mate Type 301	3	O2 / Combustibles / CO	0-30% / 0-100% LEL / 0-1000 ppm	Electrochemical / Catalytic / Electrochemical	Yes	No	No	12.7 x 7.1 x 4.1	0.6
	Safe T Mate Type 400	4	O2 / Combustibles / H2S / CO	0-30% / 0-100% LEL / 0-500 ppm / 0-1000 ppm	Electrochemical / Catalytic / Electrochemical / Electrochemical	Yes	No	No	12.7 x 7.1 x 4.1	0.6
	3220HS	3	O2 / Combustibles / H2S	0-25% / 0-100% LEL / 0-100 ppm	Electrochemical / Catalytic / Electrochemical	Yes	Yes	No	30.5 x 14.0 x 9.5	3.6
	3220CO	3	O2 / Combustibles / CO	0-25% / 0-100% LEL / 0-300 ppm	Electrochemical / Catalytic / Electrochemical	Yes	Yes	No	30.5 x 14.0 x 9.5	3.6

Table 2. (Continued).

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously[a]	Gases Monitored[b]	Concentration Range[c]	Sensor Type[d]	Simultaneous Digital Display of All Gas Levels?[e]	With Built-In Sampling Pump?[f]	With Data Logging Capability?[g]	Dimensions, L x W x H (cm)	Weight[b] (kg)
GfG Gas Electronics	Polytector G 700	4	O2	0-25%	Electrochemical	No	Yes	Yes	21.7 x 9.0 x 6.0	0.9
			Combustibles	0-100% LEL or 0-5% CCl4	Catalytic					
			Combustibles	0-99.9%	Thermal Conductivity					
			H2S	0-50 ppm	Electrochemical					
			CO	0-200 ppm	Electrochemical					
Industrial Scientific	HMX271	3	O2	0-30%	Electrochemical	No	No	No	12.1 x 7.0 x 3.8	0.6
			Combustibles	0-100% LEL	Catalytic					
			H2S	0-1999 ppm	Electrochemical					
	CMX270	3	O2	0-30%	Electrochemical	No	No	No	12.1 x 7.0 x 3.8	0.6
			CCl4	0-5%	Catalytic					
			CO	0-1999 ppm	Electrochemical					
	CMX271	3	O2	0-30%	Electrochemical	No	No	No	12.1 x 7.0 x 3.8	0.6
			Combustibles	0-100% LEL	Catalytic					
			CO	0-1999 ppm	Electrochemical					
	TMX410	4	O2	0-30%	Electrochemical	Yes	No	Yes	12.1 x 7.0 x 5.1	0.7
			CCl4	0-5%	Catalytic					
			Combustibles	0-100% LEL	Catalytic					
			H2S	0-999 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO2	0-99.9 ppm	Electrochemical					
			Cl2	0-99.9 ppm	Electrochemical					
			NO2	0-99.9 ppm	Electrochemical					

Table 2. (Continued).

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously[a]	Gases Monitored[b]	Concentration Range[c]	Sensor Type[d]	Simultaneous Digital Display of All Gas Levels?[e]	With Built-In Sampling Pump?[f]	With Data Logging Capability?[g]	Dimensions, L x W x H (cm)	Weight[b] (kg)
Lumidor Safety Products	Gasponder IV Model PGM-14	4	O2 Combustibles H2S CO	0-30% 0-100% LEL 0-100 ppm 0-400 ppm	Electrochemical Catalytic Electrochemical Electrochemical	No	Yes	No	19.7 x 12.7 x 5.4	1.4
	Gasponder MPU-33	3	O2 Combustibles CO H2S SO2	0-90% 0-100% LEL 0-700 ppm 0-100 ppm 0-100 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical	Yes	Yes	Yes	16.5 x 16.5 x 6.0	1.3
	Gasponder MPU-44	4	O2 Combustibles CO H2S SO2	0-90% 0-100% LEL 0-700 ppm 0-100 ppm 0-100 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical	Yes	Yes	Yes	16.5 x 16.5 x 6.0	1.3
	GasPro Plus MPU-16	4	O2 Combustibles CO H2S SO2	0-50% 0-100% LEL 0-800 ppm 0-800 ppm 0-20 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical	Yes	Yes	No	20.3 x 11.2 x 4.1	0.6
Miles	Compur Tritox D or M	3	O2 Combustibles H2S CO SO2 Cl2	0-30% 0-50% LEL 0-100 ppm 0-300 ppm 0-20 ppm 0-5 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical Electrochemical	No	Yes	No	24.5 x 11.0 x 4.6	1.2

Table 2. (Continued).

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously[a]	Gases Monitored[b]	Concentration Range[c]	Sensor Type[d]	Simultaneous Digital Display of All Gas Levels?[e]	With Built-In Sampling Pump?[f]	With Data Logging Capability?[g]	Dimensions, L x W x H (cm)	Weight[h] (kg)
MSA	Model 360	3	O2 Combustibles CO	0-25% 0-100% LEL 0-500 ppm	Electrochemical Catalytic Electrochemical	No	Yes	No	25.4 x 17.8 x 9.5	3.4
	Model 361	3	O2 Combustibles H2S	0-25% 0-100% LFL 0-50 ppm	Electrochemical Catalytic Electrochemical	No	Yes	No	25.4 x 17.8 x 9.5	3.4
	MiniGard III	3	O2 Combustibles H2S CO	0-25% 0-5% CH4 or 0-100% CSH2 0-50 ppm 0-500 ppm	Electrochemical Catalytic Electrochemical Electrochemical	No	Yes	No	17.8 x 8.9 x 4.3	0.6
	Passport	5	O2 Combustibles H2S CO SO2 Cl2 NO NO2 HCN HCl	0-25% 0-100% LEL or 0-5% CH4 0-50 ppm 0-1000 ppm 0-20 ppm 0-20 ppm 0-1000 ppm 0-20 ppm 0-100 ppm 0-100 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical Electrochemical Electrochemical Electrochemical Electrochemical Electrochemical	Yes	Yes	Yes	20.6 x 8.3 x 4.8	0.8
National Draeger	Trialarm	3	O2 Combustibles H2S CO	0-25% 0-100% LEL 0-200 ppm 0-999 ppm	Electrochemical Catalytic Electrochemical Electrochemical	No	No	No	18.0 x 8.5 x 4.5	0.7
	Multiwarn	3	O2 Combustibles H2S CO	0-25% 0-100% LEL 0-200 ppm 0-500 ppm	Electrochemical Catalytic Electrochemical Electrochemical	Yes	Yes	Yes	12.4 x 19.0 x 6.3	1.4
	Quadalarm	4	O2 Combustibles H2S CO	0-25% 0-100% LEL 0-200 ppm 0-999 ppm	Electrochemical Catalytic Electrochemical Electrochemical	No	No	No	18.0 x 8.5 x 4.5	0.7

Table 2. (Continued).

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously[a]	Gases Monitored[b]	Concentration Range[c]	Sensor Type[d]	Simultaneous Digital Display of All Gas Levels?[e]	With Built-In Sampling Pump?[f]	With Data Logging Capability?[g]	Dimensions, L x W x H (cm)	Weight[h] (kg)
Neotronics	MiniGas	3	O2	0-25%	Electrochemical	No	No	No	16.2 x 7.2 x 4.2	0.9
			Combustibles	0.99% LEL or 0.05 to 4.95%	Catalytic					
			H2S	0-499 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
	Exotox 40	4	O2	0-35%	Electrochemical	No	No	No	17.8 x 10.2 x 5.1	1.1
			Combustibles	0.99% LEL	Catalytic					
			H2S	0-499 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO2	0-99.9 ppm	Electrochemical					
	Exotox 50	4	O2	0-32%	Electrochemical	No	No	No	20.3 x 10.2 x 5.8	1.4
			Combustibles	0.99% LEL	Catalytic					
			H2S	0-499 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO2	0-99.9 ppm	Electrochemical					
			CO2	0-5.0%	Electrochemical					
	Exotox 55	4	O2	0-32%	Electrochemical	No	No	Yes	20.3 x 10.2 x 5.8	1.4
			Combustibles	0.99% LEL	Catalytic					
			H2S	0-499 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO2	0-99.9 ppm	Electrochemical					
	Exotox 60	5	O2	0-32%	Electrochemical	Yes	Yes	No	16.0 x 11.0 x 8.0	1.0
			Combustibles	0-100% LEL or 0-5%	Catalytic					
			H2S	0-499 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO2	0-99.9 ppm	Electrochemical					
			NO2	0-99.9 ppm	Electrochemical					
			Cl2	0-99.9 ppm	Electrochemical					
	Exotox 75	5	O2	0-32%	Electrochemical	Yes	Yes	Yes	16.0 x 11.0 x 8.0	1.0
			Combustibles	0-100% LEL or 0-5%	Catalytic					
			H2S	0-499 ppm	Electrochemical					
			CO	0-999 ppm	Electrochemical					
			SO2	0-99.9 ppm	Electrochemical					
			NO2	0-99.9 ppm	Electrochemical					
			Cl2	0-99.9 ppm	Electrochemical					

Table 2. (Continued).

Manufacturer Or Distributor	Model Series	Maximum Number Of Sensors That Can Be Installed Simultaneously[a]	Gases Monitored[b]	Concentration Range[c]	Sensor Type[d]	Simultaneous Digital Display of All Gas Levels?[e]	With Built-In Sampling Pump?[f]	With Data Logging Capability?[g]	Dimensions, LxWxH (cm)	Weight[h] (kg)
Scott Aviation	S108	3	O2 Combustibles H2S	0-25% 0-100% LEL 0-199 ppm	Electrochemical Catalytic Electrochemical	No	No	No	15.9 x 7.9 x 4.1	0.5
	S109	3	O2 Combustibles CO	0-25% 0-100% LEL 0-199 ppm	Electrochemical Catalytic Electrochemical	No	No	No	15.9 x 7.9 x 4.1	0.5
Sieger	Gas Leader	4	O2 Combustibles H2S CO SO2 Cl2 NO NO2 HC	0-25% 0-100% LEL 0-500 ppm 0-20 ppm 0-10 ppm 0-100 ppm 0-20 ppm 0-2000 ppm	Electrochemical Catalytic Electrochemical Electrochemical Electrochemical Electrochemical Electrochemical Electrochemical Electrochemical	Yes	No	Yes	19.0 x 18.0 x 6.0	1.7

[a] The maximum number of sensors that can be installed simultaneously does not necessarily equal the total number of gases that the instrument can monitor. Normally, for instruments which can accommodate more than three sensors simultaneously, the user has a choice of which toxic gas(es) to monitor.

[b] O_2 = Oxygen; H_2S = Hydrogen Sulfide; CO = Carbon Monoxide; CO_2 = Carbon Dioxide; SO_2 = Sulfur Dioxide; Cl_2 = Chlorine; NO = Nitrogen Monoxide or Nitric Oxide; NO_2 = Nitrogen Dioxide; H_2 = Hydrogen; HCN = Hydrogen Cyanide; HCl = Hydrogen Chloride; NH_3 = Ammonia.

[c] % = percent by volume; %LEL = percent of the Lower Explosion Limit (LEL); CH_4 = Methane; C_5H_{12} = Pentane; ppm = Parts per million.

[d] MOS = Metal Oxide Semiconductor sensor; Catalytic = Catalytic combustion sensor. For more information about the different sensor types listed, refer to reference (5).

[e] Read-out is digital, unless indicated otherwise.

[f] Determining whether or not the device has a built-in sampling pump is ambiguous since in some models an "external" pump can be clipped or attached onto the instrument and be powered by the monitor's battery pack. However, all the models can be purchased with an optional sampling pump. Hence, all the instruments listed can be used for confined area monitoring.

[g] Data logging capability is not a necessity for confined atmosphere monitoring.

[h] The weights indicated are approximate values since it is not known what battery pack or sensors were installed.

[i] The CGM-929 monitor supposedly has an MOS sensor which responds to hundreds of toxic gases.

[j] All CGS series instruments are available with an "industrial calibration", set up for toxic and combustible levels of hydrocarbons.